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## THE STRENGTH OF THE EARTH'S CRUST

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### PART V. THE DEPTH OF MASSES PRODUCING GRAVITY ANOMALIES AND DEFLECTION RESIDUALS

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#### DEPTHS INDICATED BY THE MAP OF DEFLECTION RESIDUALS

*General relations shown by deflections.*—Hayford gives a plate[1] which shows all the residuals of Solution H. These are laid off as arrows and show graphically the magnitude and direction of the portions of the deflections which are outstanding after allowance is made for the deflections calculated according to Solution H. They therefore show the excesses or deficiencies of mass in the crust

[1] *Supplementary Paper*, illustration No. 3; also Bowie, 1912, illustration No. 5.

as measured against the demands of the hypotheses made in that solution. In Fig. 12A is reproduced a portion of Hayford's chart. A general inspection of the map of the residuals of Solution H shows that many of the large deflections of opposite sign lie comparatively close together. On a line connecting two stations, $Fx$ is the component of the deflection which lies in that line, $Fy$ is the component at right angles to that line. In most cases not enough stations are located on an approximately straight line to permit well-defined curves to be drawn for $Fx$ and $Fy$. But it has been shown that for spheres and other concentrated masses the curve for $Fx$ rises steeply from zero to maximum value and sinks away more gently beyond. Even for flat disks the outer part of the deflection curve will be flatter than for the inner part. Random locations on the curve are therefore more likely to give the maximum measurement at some point beyond the real maximum rather than at some point between the epicenter and the real maximum. Using these stations giving maxima for $Fx$ as if they were at the points of real maxima will therefore give on the average too great a distance from the center to the point of real maximum $Fx$ and consequently too great a depth to the centers of attraction. Interpreting the disturbing masses as spheres is also an assumption likely to give too great a depth, as is indicated later. Minor centers of outstanding mass will affect the positions of the points of maximum value, but in a sufficient number of examples this effect will largely cancel out. The tabulation of the distances measured from Hayford's map between ten pairs of notable $Fx$ maxima is given in Table XXVII.

It is seen that the distance between these maxima is more largely dependent upon the length of the sides of the geodetic triangles than upon the depth to center of mass, since in less than half of these illustrations did a station fall between the two maxima. The distance between the real maxima is then probably somewhat greater than 86 km., the average of the six distances without intervening stations, but is probably somewhat under the general mean of 110 km. This mean distance of 110 km. between ten notable maxima of $Fx$ corresponds to a mean depth of spheres of 79 km. Considering the various assumptions made, it is seen that

the mean depth of masses producing these deflections is probably much less than 79 km. They belong, therefore, to the outer half of the zone of compensation.

TABLE XXVII

DISTANCES BETWEEN ADJACENT LARGE DEFLECTIONS OF OPPOSITE SIGN

| Locality of Mass | Sign of Mass | Numbers of Stations | Stations between | Distances between in Km. |
|---|---|---|---|---|
| New Jersey | + | 255–142 | 0 | 110 |
| Kentucky–Ohio | + | 85–84 | 0 | 100 |
| Georgia–Florida | + | 292–294 | 1 | 160 |
| Florida | + | 299–300 | 0 | 145 |
| Michigan–Indiana | + | 344–346 | 1 | 165 |
| Illinois | + | 75–74 | 0 | 90 |
| Nebraska | + | 327–329 | 1 | 170 |
| Colorado | − | 59–57 | 1 | 100 |
| California | − | 238–236 | 0 | 50 |
| California | − | 245–246 | 0 | 22 |
| | | | Mean | 110 |

There are other areas, however, as in the Adirondacks, Maine, Michigan, and the Great Basin, where the distance between the large deflections of opposite sign is considerably greater. So far as this relation goes they could be due either to broad outstanding masses in the zone of compensation or to much greater but more concentrated masses in the nucleus beneath. But the general relations to the magnitude and location of the gravity anomalies as discussed later under that subject suggest that in so far as the evidence is determinative these broader areas are also due to broad excesses or deficiencies in the outer crust, not to masses in the centrosphere. The data are not, however, in all areas of a sufficiently complete nature to give determinate solutions. In other areas, however, detailed study following the lines of criteria previously developed can bring out very definite results in regard to the location and depth of masses in spite of the interference of the fields of force from various centers. An example of what may be done by a detailed examination is shown under the next topic.

*Detailed study of the Texas–Kansas region.*—Fig. 12A shows the deflections as given on a north-south line of triangulation 1,000 km. in length. The gravity anomalies are shown for distances of 200 km. on each side of the traverse. The stations are sufficient in

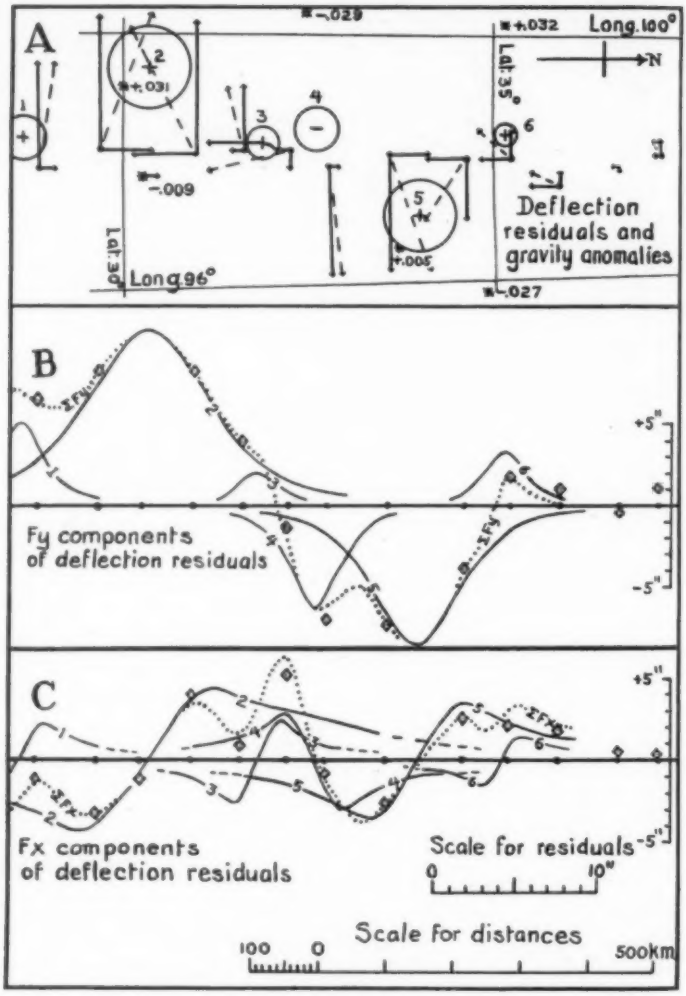


FIG. 12.—Residuals of Solution H and gravity anomalies in Texas, Oklahoma, and Kansas, with the interpretation of the outstanding masses in terms of equivalent spheres.

number and sufficiently close to a straight line to permit the application of the principles previously discussed.

The residuals are given in the north-south and east-west directions. The broken lines give the resultants. Their convergence indicates that there are two large and controlling positive masses marked on the map as 2 and 5. To account for the local variations shown by the resultants from station to station it is necessary, however, to locate smaller masses of positive or negative nature approximately as shown at 1, 3, 4, and 6. There must be of course many other centers of moderate disturbance within the area of 400,000 km. which is shown, but such as exist are far enough from the line of section not to exert an appreciable influence. It is noteworthy that gravity stations only 200 km. from the line of the traverse can show anomalies as large as −0.029, +0.032, and −0.027 dyne without the masses which give these anomalies showing appreciable control over the deflections on the line of traverse. Their areas of influence are therefore restricted. The limited influence of these masses giving anomalies somewhat above the average and at a moderate distance, and the small masses locally modifying the deflections both serve to show the importance of nearness of location. This limitation of control over the deflections, restricted to distances of less than 100 to 200 km., is itself an indication that these outstanding masses lie within the zone of compensation, otherwise their effects would be more far-reaching.

The residuals permit, however, a much more detailed solution to be made. As a first approximation assume the outstanding masses to be spheres. Figs. 12B and 12C. show the results. This is not merely an arbitrary adjustment of curves and one of a number which might be devised. On the contrary, it has been shown in the discussion of Section A and especially in Fig. 11 that the ratio of the two maxima of the deflection components, $Fy$ and $Fx$, and the ratio of $EE'$ to $E'M$ hold a definite relation to the distance and depth of the center of the sphere. Therefore if curve 2 be drawn in proper proportion and as shown in B in order to satisfy the demands of the $y$ component, then the maximum value of $Fx$ must not be over 40 per cent of the maximum value for $Fy$, even if the center

of mass is close to the surface. It may be any value less than 40 per cent of maximum *Fy*, according to the depth of the center. But having chosen that ratio which appears to fit the demands of the data, the distance of the point of maximum *Fx* from the point of zero value becomes also fixed. The curves numbered 2 in Figs. 12B and C must therefore satisfy between them the demands of the ratios shown in Figs. 11E and F. The value of *EE'* as deduced from either curve must be the same.

The sum of all the *Fy* curves in 12B is marked $\Sigma$ *Fy* and must pass through, or close to, the points which measure the values given by the deflection residuals. These points are shown as small rectangles in B and C and give ordinates which correspond with the size of the components of the residuals as shown in A. In drawing B and C the adjustment of the curves to give the proper values to $\Sigma$ *Fy* and $\Sigma$ *Fx* resulted in a slight readjustment of the centers of mass as shown in A. The positions as shown in Fig. 12A have been determined from the curves below, and their approximate agreement with the initial indications of the resultants is a check on the validity of the solution. It is seen that the epicenter of a mass should not lie on the exact intersection of any two resultants, since at the point of measurement several masses have an appreciable influence upon the direction of the resultant. The adjustment of the curves is therefore the best way of determining finally the best location of the epicenters.

The measurement of these curves gives the tabulation of data shown in Table XXVIII.

The depth to the centers of the equivalent spheres having been solved by means of the ratios given in Figs. 11E and 11F, the masses of these spheres are ascertained as follows. In Fig. 11 the value of the maximum deflections for *Fy* and *Fx* due to the unit sphere are shown for various distances of the section line from the epicenter. For example, for $EE' = 1.5D$, max. *Fy* is 4.6″. Now for sphere No. 4, Fig. 12A, $EE' = 1.5D_4$ and the max. *Fy* is 6.2″. But *D* for the unit sphere is 64 km. whereas $D_4$ is 31 km. Now the magnitude of the deflections for points similarly situated in two fields of gravitative force will vary directly as the respective masses and inversely with the squares of the distances. This may be put into

a formula as follows: Let there be two masses $M$ and $M_n$ with centers at depths $D$ and $D_n$; below a horizontal plane. For points on the plane similarly situated with respect to their respective centers let the components of the deflection force be $Fy$ and $Fx$ for the one, $Fy_n$ and $Fx_n$ for the other. Then

$$M_n = \frac{Fy_n D_n^2}{FyD^2} M; \quad \text{also } M_n = \frac{Fx_n D_n^2}{FxD^2} M$$

The results of the application of this formula are shown in the last column of Table XXVIII. They have been carried out to two significant figures, but the second is not to be regarded as accurate,

TABLE XXVIII

INTERPRETATION OF RESIDUALS IN TERMS OF EQUIVALENT SPHERES

| No. of Sphere | Data: From Fig. 12 Max. $Fy$ | Max. $Fx$ | Max. $Fy$ / Max. $Fx$ | Fig. 11F $EE'$ in Terms of $D$ | Data: From Fig. 12 $EE'$ | $E'M$ | $\frac{EE'}{E'M}$ | Fig. 11E $EE'$ in Terms of $D$ | Results: Depth in Km. | Mass in Terms of Unit Sphere Whose $R=50$ km. $d=0.1$. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5.1 | 2.3 | 2.20 | $1.7D_1$ | 42 | 35 | 1.20 | $1.7D_1$ | 25 | $+0.20M$ |
| 2 | 10.8 | 4.4 | 2.46 | $3.0D_2$ | 125 | 95 | 1.31 | $2.5D_2$ | 40 to 50 | $+2.5$ to $2.0M$ |
| 3 | 2.0 | 2.5 | 0.80 | $0.3D_3$ | 13 | 33 | 0.40 | $0.3D_3$ | 43 | $+0.17M$ |
| 4 | 6.2 | 2.9 | 2.13 | $1.5D_4$ | 47 | 40 | 1.17 | $1.5D_4$ | 31 | $-0.32M$ |
| 5 | 8.4 | 3.5 | 2.40 | $2.5D_5$ | 88 | 67 | 1.31 | $2.5D_5$ | 35 | $+1.10M$ |
| 6 | 3.3 | 1.4 | 2.35 | $2.2D_6$ | 34 | 27 | 1.27 | $2.2D_6$ | 16 | $+0.07M$ |

even if the original data are accurate to the second place. This is because the error of the square of a quantity is approximately twice as great as the original error, and for values $EE'$ above $1.0D$ the error in even the first power of $D$ is appreciably greater than the error in the measured quantities. This of course is a consideration of the error in the determination of the depth and mass of the hypothetical spheres, not a consideration of the errors in the deflections themselves, nor related to the fact that the masses are in reality not spheres.

It has been shown previously that the interpretation of the outstanding masses in terms of spheres will give depths too great unless the real masses have their greatest dimension vertical. For the same reasons the hypothetical spheres will be of greater mass

than the real horizontally extended bodies in order to produce the same deflections as those observed.

The question arises then as to the real form and mass of the bodies interpreted here as spheres. The supplemental data at hand yield evidence only in regard to No. 2. This, however, is the greatest of the six outstanding masses in this series. The supplemental data consist of observations on gravity anomalies at three localities whose distances from the epicenter of No. 2 are as follows:

RELATIONS OF GRAVITY ANOMALIES TO THE EPICENTER OF MASS NO. 2

| | |
|---|---|
| *a*, 47 km. S. E. | +0.031 |
| *b*, 163 km. E. | −0.009 |
| *c*, 250 km. N.N.W. | −0.029 |

Now the curves for *Fv* and also for the *Fy* component of *Fh* show with increasing distance from the epicenter a rapid fall from the maximum value. These effects of the gravitative force due to outstanding masses are consequently markedly local and the nature of the mass No. 2 must have a distribution such as to account for the anomaly of +0.031 at 47 km. from the epicenter. The interpretation must not give a form which will exert marked influence upon those points distant 163 and 250 km. The dominating influence of mass No. 2 on the value of *Fv* appears therefore to be confined to distances within 125 or 150 km. of the epicenter. But the two limiting spheres of mass $2.5M$ and $2.9M$ respectively give the relations shown in the first two lines of Table XXIX.

TABLE XXIX

INTERPRETATION OF MASS NO. 2

| Form | Mass in Terms of Unit Sphere | Depth to Center in Km. | Radius in Km. | Height in Km. | Excess Density Above Mean | *Fv* at Epicenter in Dynes | *Fv* at 47 Km. in Dynes |
|---|---|---|---|---|---|---|---|
| A. Sphere..... | 2.5 | 40 | 40 | 80 | 0.5 | 0.542 | 0.148 |
| B. Sphere..... | 2.9 | 50 | 50 | 100 | 0.3 | 0.405 | 0.157 |
| C. Cylinder.... | 2.5 | 40 | 200 | 10.4 | 0.1 | 0.035 | ..... |
| D. Cylinder.... | 0.6 | 20 | 100 | 5.2 | 0.2 | 0.035 | ..... |

The interpretation of the deflections as due to spheres gives a gravity anomaly at the epicenter of the sphere between four and six times larger than the largest yet observed in the United States.

At the distance of 47 km. the anomaly would be from 0.148 to 0.157 dyne, five times the observed value of 0.031. Clearly then the initial interpretation as a sphere, although it satisfies the deflection residuals of the line of traverse, is far from the truth. The mass must have horizontal dimensions much greater than the vertical. Assume for trial that the mass has the form of a vertical cylinder with the same mass and depth to center as the sphere, but of a proportion of height to breadth which shall satisfy approximately the gravity anomaly. The result is shown in the third line of Table XXIX. The gravity anomaly of 0.035 at the epicenter would correspond in a cylinder of these proportions to a value only slightly less at 47 km. But the radius of the cylinder, 200 km., is now far too great. Other cylinders of similar form will, however, give the same anomaly at the epicenter if the depth and dimensions are all divided by any number, $n$, and the density multiplied by the same number. This gives a series of similar cylinders in which the density varies inversely with the dimensions. Of such a series that shown in the fourth line, obtained by giving $n$ a value of 2, comes fairly close to satisfying all the requirements. The exact degree of adjustment which would be needed to satisfy both the gravity anomaly at 47 km. and the deflections on the line of traverse has not been calculated. If this were done and the dimensions adjusted accordingly, it would complete a second approximation to the real form and mass of No. 2. Such an extended treatment of the subject would, however, be beyond the immediate purposes of this article and beyond the limits of space which it should occupy. The data also are at present hardly of a sort which would justify further computations. It should be emphasized, however, that such a complete investigation is not difficult and would require but little further data, properly chosen, to check the conclusions.

In the first approximation, the mass was assumed to have a uniform distribution about a center, giving a sphere. In the second approximation, the vertical axis is assumed to be different from the horizontal axes, but the latter being kept alike, the horizontal section would still be a circle. A single observation of the gravity anomaly near the epicenter suffices to give this second approximation. The third approximation would be to consider the three

co-ordinate axes of the mass unlike. This would require some observations in two directions at right angles from the epicenter. More complete data consisting of both deflection and gravity observations would of course give still closer approximations toward the real form and depth of the mass. What it is desired to show here, however, is that the interpretation of this large mass as a sphere gave a depth to the center of mass about twice too great and a mass perhaps four times too great. This result is in line with the general deduction previously made in regard to the direction of the error involved in the interpretation of deflection residuals as due to spheres. It contributes its individual testimony to show that the masses producing the notable gravity anomalies and deflection residuals are situated within the zone of isostatic compensation and more especially in the upper part of that zone.

In regard to the large positive mass No. 5 the data are less determinative. At a distance of 60 km. southeast from the epicenter the anomaly is only +0.005 dyne. At 150 km. northeast it is −0.027 dyne. It thus appears that there are some large negative masses easterly of No. 5. As this, however, is on the side away from the line of traverse the problem of the real form and mass of No. 5 is at present indeterminate.

The adjustment between the deflection curves due to spherical masses and the values of the deflection residuals has been made closer, perhaps, than the probable values of the residuals. Furthermore, the residuals of Solution G, if they had been given for this region, would have required a somewhat different distribution of masses. A solution for that depth of compensation which would reduce to the smallest quantity the sum of the least squares of the residuals of this area 1,000 km. long and 400 km. wide would be still somewhat different. That local solution which would give the smallest residuals would be such as would make small the algebraic sum of the positive and negative masses, but the difference in mass between positive and negative centers would not be much reduced. The depth to the centers of mass would be the quantity most affected by a change in the hypothesis regarding the depth of compensation. These epicenters then, in so far as the accidental errors do not vitiate the values of the residuals, are realities in nature.

In view of this analysis of the data given in Fig. 12 and in Table XXVIII, it is to be concluded that for this region even the larger outstanding masses from Solution H, capable of exerting a notable influence on the *Fx* component of the deflections to a distance of 400 km. or more, appear to have their centers not deeper than 20–25 km. Their mass is consequently within the outer half or even the other third of the zone of isostatic compensation as given by Solution H. There is further no evidence of centrospheric heterogeneity.

OTHER INDICATIONS REGARDING DEPTH OF OUTSTANDING MASSES

*Deflections by linear or dike-like masses.*—The resultants of the deflection residuals are shown by broken lines in Fig. 12. They show a tendency to converge toward centers. This is true in general for the whole United States, as shown in Hayford's illustration. This tendency to convergence indicates that the dominating outstanding masses may usually be regarded in a first or second approximation as symmetrical with respect to a vertical axis. In contrast, however, to this rule the residuals of Solution H in the vicinity of Washington[1] indicate an outstanding mass with a northeast-southwest extension of at least 120 km., whereas the breadth is probably not more than 20 km. This narrowness is shown by the limited distance between the large residuals of opposite sign in a northwest-southeast direction. The linear extension is shown by the parallel rather than radial arrangement of the resultants. The mass gives rise to large deflections for a distance of as great as 100 km. from the sides, but its influence dies out somewhat beyond.

It is clear from these relations that the assumption of a form of the mass symmetrical about a vertical axis for the purpose of determining the depth of the center would not be justifiable. Other assumptions which might be made in order to subject the mass to mathematical investigation would be to consider it as a horizontal prolate spheroid, or as a horizontal linear mass at a certain depth, cylindriform, or as a vertical plate. The latter would be preferable. For a quantitative solution of its dimensions and mass it would be desirable to have some observations farther to the northwest.

[1] Hayford, Supplementary Paper, illustration No. 4.

The following qualitative conclusions may, however, be drawn from an inspection of the residuals.

Maximum deflections are found on each side of the axial line not more than 40 km. distant. The deflections continue large for at least twice this distance but not for three times this distance. The existence of large residuals so close to the axial line shows conclusively that the outstanding mass is within the zone of compensation and apparently within its outer half, but the maintenance of the size of the deflections without much change for a considerably greater distance shows also that it is not merely a surficial and linear mass. It must have considerable extension in depth. In these indications it agrees therefore with the more precise solution of limiting depth given for the Texas-Kansas region.

*Indeterminate evidence from anomaly contours.*—The map of anomaly contours shown in Fig. 5, Part II, and reduced from Bowie, does not in general throw positive light on the depth of the masses which produce the anomalies of gravity. The necessarily generalized and smoothed-out character of this map has been discussed previously, especially in Part IV. A map based upon more numerous observations would show higher values of maximum anomaly and more of them. The centers of outstanding mass and the anomaly gradients would become better defined, and the distances from epicenter to half value of $Fv$ would average smaller than shown at present. However, notwithstanding the defects, thirty-two measurements were made on this map of the distances from fifteen pronounced maxima to the anomaly contour of half value, and in directions not toward other adjacent maxima. This distance was chiefly controlled therefore by the single dominating mass. The measurements gave an average distance of 120 km.

If the outstanding masses which gave these anomalies were assumed to have the form of spheres, this would give their centers a depth of 160 km. and imply the existence of marked heterogeneity extending below the zone of compensation as given by Solution H. If the average form were assumed, however, to be that oblate mass shown in Fig. 9C, this distance to the contour of half value would correspond to a depth of 100 km. But such assumptions as to form are hypothetical and justifiable only as a step in successive

approximations, not as a conclusion. The anomalies can be accounted for just as readily by an assumption of much shallower depths. The outstanding masses would then possess marked thinness in comparison with their breadth. They would be horizontally extended masses or the algebraic sum of many masses; in either case they could lie within a quarter of the depth indicated by the assumption of spherical form. The mere measurement of the mean distance from epicenter to half value of $Fv$ is therefore wholly indeterminate except as regards the limits of regional compensation. In some respects, however, the present map does give suggestions. Let the attention be turned to these individual features.

A line of stations extends along the margin of the Coastal Plain from Washington, D.C., to Hoboken, New Jersey. The anomalies at the stations and their distances apart as measured on the map are as follows:

No. 22. Washington, D.C., +0.039 dyne
58 km.
No. 23. Baltimore, Md., −0.011
138 km.
No. 24. Philadelphia, Pa., +0.022
61 km.
No. 25. Princeton, N.J., −0.019
69 km.
No. 26. Hoboken, N.J., +0.024

This line of stations extends in the direction of the trend of the foundation rocks, yet the sign is reversed at every station, showing marked heterogeneity even in the direction of the strike. The average anomaly without regard to sign is 0.023, a little larger than the average for the whole United States. The average with respect to sign is +0.011. As there is only one station for each of the positive and negative masses the positions and magnitudes of the real maxima and the curves of changing anomaly are unknown. Masses in the upper half of the zone of compensation could produce these effects at these horizontal distances with but little mutual neutralization. Masses below the zone of compensation would, however, have to be very great, not only because the force decreases inversely with the square of the distance, but because masses of opposite sign whose centers are more than 120 km. deep and situated but

from 60 to 70 km. apart would largely neutralize each other in their surface effects. Furthermore, there is no notable extension of the anomaly contours shown in any direction, and more especially at right angles to the line of stations, such as would suggest the wider fields of force due to deep-seated masses. If the masses were at great depth this limitation of attraction to regions near the epicenters could be produced only by a special checkerboard arrangement of opposite masses in all directions. It may be rather firmly concluded, therefore that the anomalies of this chain of stations along a line of low topographic relief are due to heterogeneities of density within the zone of compensation.

In certain regions, as in Florida, in western New York and Pennsylvania, and in the Great Basin, occur broad areas of anomaly showing no central maximum. To some extent this is doubtless due to incompleteness of observations, but in the areas mentioned the stations are so spaced as to show that even if the map were complete there would not exist marked domes of anomaly, such as those central at Minneapolis, Minnesota, and at Lead, South Dakota. This absence of domal form of anomaly curves suggests that the disturbing masses cannot be below the zone of compensation, but should be interpreted as due to the effects of masses widely distributed in the zone of compensation. This relation is especially striking in southern Nevada. The deflection residuals in northern Utah and Nevada all turn away from this southern area of defective mass, shown in Fig. 5, Part II, of this article, as located by Hayford and Bowie. Yet within this broad area of defective mass Station No. 67 shows an anomaly of only $-0.013$ and some of the surrounding anomalies have actually a larger negative value. There is here then an entire absence of a broad domal form. This is the region which indicates from the least-square equations of the deflections of the vertical the shallowest compensation within the United States; and the combination of the evidence from deflection residuals and anomaly contours goes to show that the anomalies are due to departures from isostasy within that shallow zone.

An inspection of Fig. 5, Part II, shows furthermore that the centers of plus and minus attraction as located by Hayford and Bowie from the deflections of the vertical, although in general

agreement with the measurements of gravity anomalies, so far as the positive or negative sign of the center of mass is concerned, yet are not closely related to the large maxima. They are, in fact, in most cases decidedly eccentric to the anomaly contours. The scarcity of these areas is a result of incompleteness of observations, but their eccentric position and association with areas of moderate anomaly is not an error due to the reconnaissance nature of the studies. These relations indicate that the neighboring regions giving broad domal areas of anomaly are in such cases not due to the dominating control of centrospheric heterogeneity, for in that case the resultants of the deflection residuals would point over broad areas in the general direction of the epicenter of the mass. The degree of discordance between the centers of dominant anomaly and centers of dominant deflection indicates that fuller observations, would produce agreement by adding to the number of such centers. The present data suggest therefore that the areas of broad excess or defect of mass as shown by the anomaly map are due to aggregates more or less composite and shallow, so that each part influences individually to some extent the direction of the deflection residuals about it. Special combinations of masses of shallow depth with other masses below the zone of compensation could, however, also account for the effects. The data of the present map of gravity anomalies are therefore largely indeterminate, but the probabilities point toward at least the greater part of the outstanding masses lying well within the zone of compensation. In this conclusion the data agree with the other lines of evidence.

### RELATION OF DEPTH OF OUTSTANDING MASSES TO HYPOTHESES REGARDING DISTRIBUTION OF COMPENSATION

The measurements of the deflection residuals are very much more detailed than are those of gravity anomalies. The evidence from them is rather conclusive that, for the regions investigated, the excesses or defects of mass which cause those residuals are situated within the zone of compensation and more especially in its outer half or third. Even if centers of outstanding mass were uniformly distributed, however, with respect to depth, they would lose influence in proportion to the square of their depth. Smaller

masses which would exert a very appreciable effect if near the surface would, in consequence, not betray their existence if situated near the base of the zone of compensation. But the larger masses which are found to exist would exert a very visible control upon the deflections of the vertical, even if their centers were at a depth of 100–200 km. The fact that such depths have not been found suggests that the larger variations from the mean density within any one earth shell tend to occur in the outer half of the zone of compensation rather than in its deeper parts or immediately below it.

As a step toward the interpretation of the evidence, let the conclusion reached in Part II of this article be accepted: that regional isostasy for ordinary relief certainly extends to a radius of 100 and probably to 150 or 200 km. Even these limits do not reach the capacity of crustal strength. Such regional limits would not in reality be subject to sharp boundaries. This agrees with the evidence of geology in showing that mountain groups of circumdenudation—those whose relief is due to erosion and not to original differential vertical movement—are upheld by the rigidity of the crust. This applies to many of the mountain groups of the Appalachians; such, for example, as the Catskills.

The fairest initial hypothesis of isostatic compensation would be then to calculate for each station the average elevation of the country within a radius of 99 km., being the outer radius of zone N, and to assume a uniform density to these limits such as is needed to compensate this area. A second trial hypothesis would be to use as the radius of regional compensation the outer limits of zone O, 166.7 km. Under these two calculations for regional compensation the Catskills would be regarded as producing deflections which should show an excess of mass at the surface of the earth. Such an erosion basin as the Nashville basin should show, on the other hand, by its deflections a surface deficiency of mass. For the hypothesis which approaches nearest to the truth, the residuals of the deflections should be small and the outstanding masses would be determined by variations of density within the crust and not of the topography upon its surface.

Under the hypothesis of local compensation as given in Solution H the excess of mass in the Catskills would show, on the contrary,

as a slightly excessive density throughout the whole zone of compensation; the Nashville basin as a slightly deficient density through the same depth. The residuals should indicate an outstanding excess and deficiency of mass respectively with the centers at a depth near the middle of the zone of compensation. But masses with centers at this depth and distance would have a very diminished maximum effect upon the residuals of the deflections of the vertical, and one largely modified by the effects of contiguous regions. Heterogeneities of density nearer the surface and not related to compensation would tend also to overshadow the error involved in the hypothesis of local compensation. It would appear then that the nature of the deflections is not very sensitive for testing the relative probability of the hypotheses of local versus regional compensation. The assistance of a computing office for trying out several hypotheses would probably bring to light, however, conclusions which would be more determinative. These statements must be regarded, therefore, as forecasts not yet subjected to the tests of computation.

In view of the preceding discussion it would seem that the deflection residuals of Solution H are chiefly of value for measuring the heterogeneities of density not related to topography, nor to the mantle of sedimentary rocks. This is especially true of the Texas–Kansas region studied in detail, for there the region is one of plains with an average elevation of about a thousand feet, and the demands of local isostasy as postulated in Solution H would call for a nearly uniform density under all this region. The outstanding masses represent in large part, therefore, real and local variations from a mean density of the continental crust.

But if masses of excess or defect of density similar to those numbered 2 and 5 of Fig. 12 were widely extended, say to a radius of 500 rather than 100 km., they would tend much more strongly to make for a local or intracontinental isostatic adjustment. They would become then not outstanding masses but in large part compensating masses. The outstanding masses represent the same kind of variations, therefore, which if more broadly extended would be in accord with an isostatic adjustment of topography to a different level. They suggest that if the zone of compensation of the continental crust be divided into three shells of 40 km. each in

thickness, the greatest variations in density take place in the outer shell. This conclusion should be regarded as tentative, however, until confirmed by wider detailed studies and more numerous examples.

Accepting for the present this tentative conclusion, how does it agree with that previously reached—that isostatic compensation in some regions appears to go notably deeper than 122 km. and that, where deep, the residuals average smaller than for the continent in general? The answer would appear to be that moderate variations of density are sufficient to account for the isostatic relations of different parts of the continent to each other and that these moderate variations may go very deep.

If the actual distribution of compensation gradually disappears with depth, the hypothesis of uniform compensation complete at a certain depth corresponds to two outstanding masses, one just above the limiting surface, 122 km. in Solution H, the other just below that surface. But these masses would largely balance each other, having opposite signs; so that they would give at the surface of the earth but little evidence of their existence. Imperfections of the hypothesis in regard to the bottom of the zone of compensation would in consequence not readily be detected by methods for determining the depth of outstanding masses.

The isostatic balance of continental crust against oceanic crust is a somewhat different problem from that of the different segments of the continent with respect to each other. Solution H requires a mean difference in specific gravity of about 0.1 to a depth of 122 km. between the crust of the average continental and average oceanic segments. The contrasts in density are therefore pronounced and go very deep. Within the continent, on the other hand, the variations in density related to isostatic compensation are comparatively small and this investigation suggests that those variations may be more largely in the higher levels of the crust.

In conclusion, the depths of the outstanding masses are seen to be related to many problems in crustal statics and dynamics. The depth determines the magnitude of the masses involved and if known will serve as a test of various hypotheses. The excesses and defects of mass departing from that mean which is demanded

by the best hypothesis will be a more accurate measure of the capacity of the rigid crust to carry without viscous yielding loads which have been borne through geologic time, hidden loads whose magnitudes in many regions appear to mask by contrast the present relief between mountains and valleys.

The measure and the meaning of the variable distribution of mass within the lithosphere constitutes an inviting field of geology, discernible in the present, but whose real exploration is a work of the future.

[*To be continued*]

# NOTES ON THE GEOLOGY OF THE SUN RIVER DISTRICT, MONTANA

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While making a geological examination last fall for the location of an irrigation dam on the North Fork of the Sun River, Montana, Professor W. O. Crosby made a careful collection of some fossils. The latter have been identified by the writers and they form the basis of these notes.

The Sun River has its origin in the Livingston Range and flows eastward to Great Falls. The district in which the fossils were collected, lies in the southern half of the Saypo atlas sheet, about 65 miles west of Great Falls. Owing to the paucity of names in this region, the Sun River is divided into a North Fork and a South Fork. These forks are in turn subdivided into North and South Forks. As only the North Fork of the Sun River is shown on the Saypo sheet, references will be made directly to the Sun River, implying the North Fork of this stream.

In the region near Milk River, about 70 miles northwest of the Sun River, Willis found one large overthrust of the Algonkian upon the Cretaceous.[1] It is probable that this overthrust divides into several smaller thrusts before reaching the Sun River.

There are nine N-S. "reefs" or ridges from the junction of the Sun River with its South Fork east to the Cretaceous plains. The indications are that each of these parallel ridges represents an overthrust to the east. Besides the field evidence of this structure is the evidence furnished by the stratigraphic position of the fossils. These were collected at too few points to show the existence of more than five faults. The fossils indicate a fault both east and west of the Dam Site. There is evidence also of a fault to the east of Arsenic Reef and of another separating the two ridges of Arsenic

[1] G. S. A. Bull. 13, 1902, p. 305–52.

Reef. The fifth is an overthrust of the easternmost reef, the Carboniferous being found to overlie the Cretaceous. The reef west of the Dam Site—Black Reef—consists of monzonite. So far as known nothing has previously been published bearing on the geology of the Saypo quadrangle.

The fossils were collected from five localities which are numbered from west to east as on the accompanying map.

*Locality 1.*—At the big bend in the South Fork of the Sun River just north of the junction of Goat Creek with this stream. Embedded in a dark arenaceous shale were found:

*Inoceramus labiatus* Schlotheim, c.[1]
*Lingula* sp. c.

The horizon is probably Coloradoan Cretaceous.

*Locality 2.*—Immediately northwest of the junction of the Sun River with its South Fork. The rock here is a shaly, fine-grained sandstone.

*Pleuromya subcompressa* Meek C.
*P. subcompressa webberensis* M. and H., r.
*Gryphaea calceola nebrascensis* M. and H., r.
*Pteria* sp. R.
*Ammonite,* R.

The horizon is Ellis (Jurassic).

*Locality 3.*—At the Dam Site, just east of the junction of the Sun River with its South Fork. The rock is a dense brownish-gray limestone. The fossils are quite thoroughly silicified.

*Syringopora surcularia* Girty, c.
*Lithostrotion whitneyi* Meek, c.
*Zaphrentis* sp., c.
*Productus semireticulatus* (Martin), R.
*Spirifer centronatus* A. Winchell, C.

The horizon is Madison (Mississippian).

*Locality 4.*—Arsenic Reef lies west of Big George Gulch. At the Sun River valley it divides into two parallel ridges. On the western ridge Professor Crosby noted *Syringopora* and *Zaphrentis* in a hard limestone. It is therefore probably Madison in age.

[1] C. indicates that the fossils collected are very abundant; c, abundant; r, rare; and R, very rare.

FIG. 1.—Map of a portion of the Saypo Quadrangle showing the fossil localities described in this paper. The localities are numbered 1 to 5.

On the eastern ridge is a softer, brownish limestone containing:

*Atrypa missouriensis* Miller, C.
*Spirifer coniculus* Girty, C.

The *Spirifer* indicates an Ouray (Devonian) age.

The *Atrypa* has been reported from the Three Forks (Devonian) shale in which it is abundant in the Yellowstone National Park area. It occurs in a finer-grained and slightly browner limestone than does the *Spirifer*. These two fossils have not been noted on the same piece of rock.

*Locality 5.*—The easternmost reef consists, according to Professor Crosby, of limestone containing the same corals—*Zaphrentis*, *Syringopora*, etc.—as are present at locality 3 and at the western ridge of Arsenic Reef, locality 4.

This limestone reef is, according to Professor Crosby, overthrust upon the Cretaceous beds to the east. One-fourth of a mile from the eastern edge of the reef a vertical drill core showed the Cretaceous shale beneath the limestone. The Cretaceous near the limestone is slightly folded, but farther east it is approximately horizontal.

# CORRELATION AND STRUCTURE OF THE PRE-CAMBRIAN FORMATIONS OF THE GWINN IRON-BEARING DISTRICT OF MICHIGAN

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Director, Michigan Geological Survey

Published information regarding the geology of the Gwinn district is very meager. In 1873, Major J. B. Brooks published[1] a brief description of the locality now occupied by the Princeton and Stegmiller mines, then known as the S. C. Smith mine, in sections 17, 18, and 20, T. 45, R. 25. In speaking of the occurrence of iron ore there he says: "The geographical position is less remarkable than what might be called its geological isolation, for it appears to be in a small patch of Huronian rocks, in the midst of a great area of barren territory, underlain by the Laurentian and Silurian systems." Brooks observed the black slate adjacent to the ore on the northeast in sections 17 and 18 and in "section 20, west of the river, a talcky schist, holding grains of quartz," but was unable to determine the stratigraphic relation of these rocks to the iron formation.

About ten years later this locality was again examined by Dr. Carl Rominger,[2] who writes as follows: "The Cheshire mine, formerly known as the S. C. Smith mine . . . . is working a strip of slaty and quartzose rock beds, known to extend along the valley of the Escanaba River for a distance of nine miles from the northwest corner of section 19, T. 46, R. 26, to the center of T. 45, R. 25." Rominger describes the rocks shown in the mining pits in sections 18 and 20, T. 45, R. 25, in considerable detail. He recognizes an iron formation underlain and overlain by slate. Owing to his misunderstanding of the structure his succession is reversed.

In 1911 the United States Geological Survey published a brief account of the geology of the Gwinn (Swanzy) district by C. R.

[1] *Michigan Geological Survey*, I, 150–51.

[2] *Ibid.*, V, (1894), Part I, pp. 70–73.

Van Hise and C. K. Leith.[1] These authors had made no detailed survey of this district and attempted merely a summary of the information from other sources available to them at the time their monograph was written. They describe the Gwinn district as a southeastern-pitching synclinorium about two miles long and from one-half to two miles wide, the structure being unknown toward the southeast because of the deep overburden. They correlate the pre-Cambrian sedimentary rocks with the Upper Huronian (Animikee) series and describe them as (1) a basal "quartz slate and quartzite grading down into arkose or decomposed granite" which is overlain by (2) the Michigamme slate carrying the Bijiki iron-bearing formation in "lenses and layers" near its base.

Recent studies by the writer for the Michigan Geological Survey based on field mapping and an examination of the records of several hundred diamond drill holes show clearly that the Gwinn district contains *at least two* unconformable series of sedimentary rocks. It seems probable that the upper series, which will be described as the Princeton series, is equivalent to the Upper Huronian of the Marquette district, that the lower series, which will be described as the Gwinn series, is equivalent to the Middle Huronian of the Marquette district, and that the Lower Huronian series, while not present in the Gwinn synclinorium, is represented by certain fragments of quartzite and cherty slate in the conglomerate at the base of the lower or Gwinn series.

Without the information afforded by records of drill holes and other exploratory operations, any statement of the geology of the Gwinn district would probably be misleading and in any event necessarily fragmentary and incomplete. Outcrops are not plentiful except in certain restricted localities and are limited to the north two-fifths of the district. The records of drill holes, carefully compiled by geologists of the Cleveland Cliffs Iron Co. and the Oliver Iron Mining Co., are the main reliance for mapping the formations. Only a few of the drill samples were seen by the writer, but each of the formations is somewhere exposed either in outcrops or in excavations and was studied on the ground. It will be seen on the

[1] C. R. Van Hise and C. K. Leith, *Monograph 52, U.S. Geological Survey*, pp. 283–86.

TABLE I

TABLE OF CORRELATIONS. MARQUETTE AND GWINN DISTRICTS

| | Marquette District—United States Geological Survey | Gwinn District—U.S. Geol. Survey, 1911 | Gwinn District—Mich. Geol. Survey, 1913 |
|---|---|---|---|
| Quaternary system | Pleistocene series—glacial drift | Pleistocene series—glacial deposits | Pleistocene series—glacial deposits |
| Ordovician system<br>Cambrian system | Unconformity<br>Upper Cambrian (Potsdam sandstone) | Unconformity<br>Limestone<br>Sandstone | Unconformity<br>Limestone and sandstone |
| Algonkian system—Keweenawan series | Unconformity<br>Not identified but probably represented by part of intrusives in Upper Huronian | Unconformity | Unconformity<br>Not identified but probably represented by basic dikes which intrude all of the pre-Cambrian formations |
| Huronian series<br>Upper Huronian | Greenstone intrusives and extrusives<br>Michigamme slate (slate and mica schist) locally represented by Clarksburg (volcanic) formation<br>Bijiki schist (iron-bearing)<br>Goodrich quartzite | Michigamme slate<br>Bijiki iron-bearing member in lenses and layers near base of Michigamme slate<br>Goodrich quartzite. Quartz slate and quartzite grading down into arkose or recomposed granite | Michigamme slate, carrying beds of ferruginous slate and chert, quartzite, and graywacke<br>Conglomerate and graywacke (Goodrich) |
| Middle Huronian | Unconformity<br>Negaunee formation (iron-bearing)<br>Siamo slate<br>Ajibik quartzite | | Unconformity<br>Iron-bearing formation and associated overlying and underlying slate (Negaunee-Siamo)<br>Arkose conglomerate, arkose and quartz-slate conglomerate (Ajibik) |

| | | | |
|---|---|---|---|
| Lower Huronian | Unconformity<br>Wewe slate<br>Kona dolomite<br>Mesnard quartzite | | |
| Archean system<br>Laurentian series | Unconformity<br>Granite, syenite, peridotite<br>Palmer gneiss | Unconformity<br>Granite | Unconformity<br>Granite and greenstone, mainly granite |
| Keewatin series | Kitchi schist and Mona schist | | |

accompanying map that information is entirely wanting in some parts of the synclinorium and in other parts is insufficient for accurate mapping. Only a few of the many faults, which certainly occur, particularly in the north end of the district, have been mapped and the exact location and character of even those is not apparent.

The lithology of the various formations will be considered only so far as essential to an understanding of the succession and the correlations, but the discussion necessarily will be more in detail than the account published in *Monograph 52*, to which reference has been made.

Preliminary to the statement of the geology, there is given in parallel columns for comparison the succession and correlation of the United States Geological Survey and of the writer.

## LOCATION AND TOPOGRAPHY, ETC.

The Gwinn synclinorium occupies an area about six miles long and from one to two miles wide, mainly in T. 45 N., R. 25 W., but extending a short distance into T. 44 N., R. 25 W. The trend of the major structure is about N. 45° W. or almost exactly parallel to the Republic trough, the southern end of which is 22 miles west and 6 miles north of the north end of the Gwinn fold. Gwinn, the principal village, is 16 miles south of the city of Marquette.

The southeast three-fifths of the Gwinn fold is buried beneath a featureless and almost flat sand plain which extends north and east to the hills of the Marquette range. In the opposite direction the surface is broken and hilly with occasional rock exposures. Granite hills encircle the northwest and north sides of the synclinorium. The district is drained by the Escanaba River, which follows the northeast side of the trough to Gwinn and then turns south across the sand plains. On the plains the water table is within a few feet of the surface and the ore bodies are deeply buried under water-saturated sand and gravel, a condition which is a serious menace to mining operations.

The first shipment of ore was made in 1872 from the Cheshire mine, now known as the Princeton No. 1 pit. About 1902 the Cleveland Cliffs Iron Co. purchased the Princeton (Swanzy,

Cheshire) mine and during the time which has since elapsed has extended its holdings by purchase and lease until it now controls all of the known workable ore bodies with the exception of the Stegmiller, which is mined by the American (Oliver) Mining Co. Since the building of the beautiful and principal village of Gwinn by the Cleveland Cliffs Iron Co. the name of the district has been changed by common usage from Swanzy to Gwinn. There are five producing mines in the district. This number will be six in 1914, and probably eight in 1915. Concrete shafts have been sunk to two additional ore bodies but it is not known when these will be equipped for mining operations.

### NOTES ON THE STRUCTURE OF THE GWINN SYNCLINORIUM

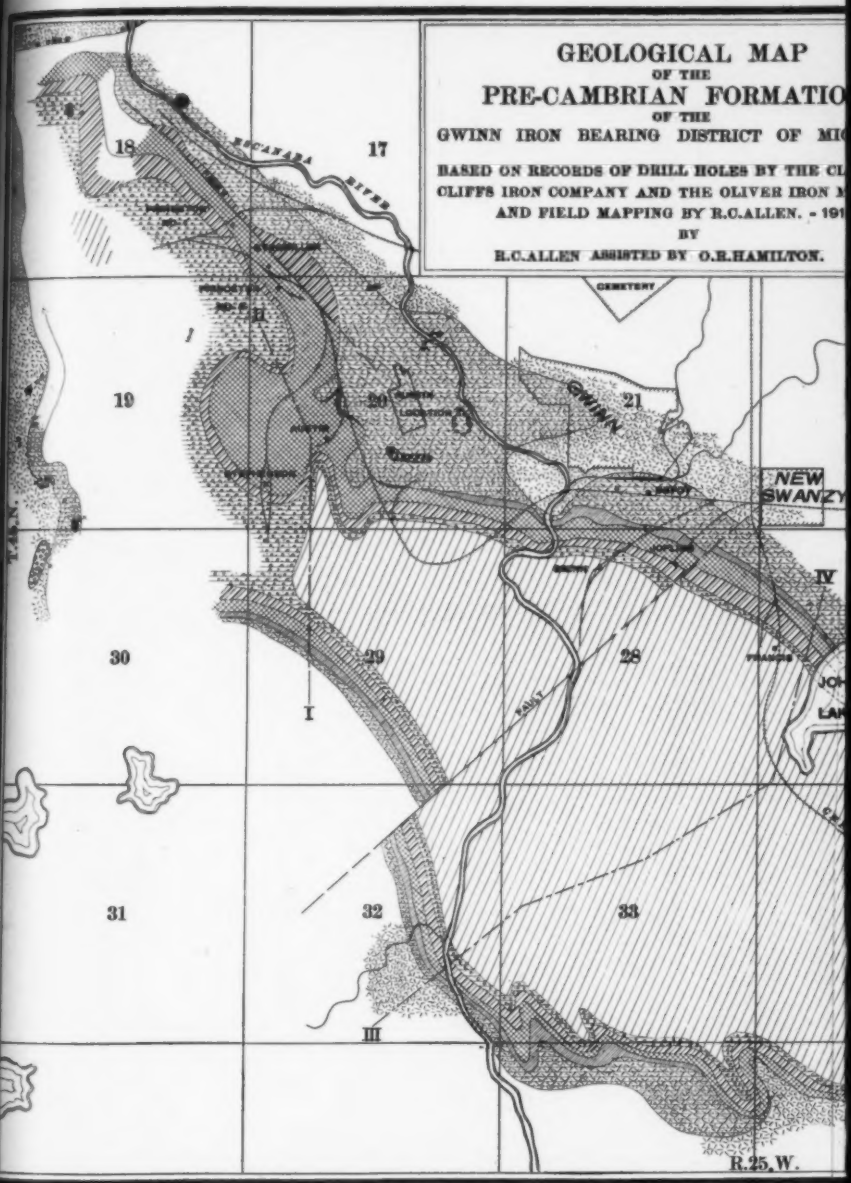
The Gwinn synclinorium contains two unconformable series of sedimentary rocks, having a combined thickness of from 800 to 1,000 ft. Outliers of flat-lying Paleozoic (Cambrian or Ordovician) sandstone and limestone occur throughout this area. The pre-Cambrian beds are remnants of formations, originally much more extensive, which have escaped erosion by downfolding or depression in the Archean basement.

The synclinorium is constricted to not more than three-fourths of a mile in width in the vicinity of the N.W. $\frac{1}{4}$ of section 29, T. 45, R. 25. North of the constricted portion, the rocks are folded and faulted in a complex manner but south of it the structure is apparently somewhat less complicated.

The southern three-fifths of the synclinorium is a spoon-shaped basin four miles long with a maximum width of about two miles. The deepest part of the fold is adjacent to the northeast limb where the Archean granite is reached in many drill holes at depths of from 1,000 to 1,200 ft. (see cross-section III–IV). Drilling along the southwest limb indicates a number of sharp drag folds pitching northwest. The folds on the opposite limb are not so sharp and are apparently simple cross-folds. The most prominent one appears in the S.E. $\frac{1}{4}$ of section 35. The synclinorium practically terminates against a faulted zone on the southeast. It is not possible to determine from present information the full extent of this zone nor the character of the faulting. The rocks in the faulted area are largely

slate, chert, conglomerate, and breccia resembling lithologically the succession in the upper or Princeton series, but the regular succession of formations shown on both limbs of the fold terminates abruptly at the line indicated as a fault on the map. Another cross-fault probably trends diagonally northeast through section 28, producing a horizontal displacement of not less than 700 or 800 ft. in the N.E. $\frac{1}{4}$ of section 32 and from 150 to 200 ft. in the N. $\frac{1}{2}$ of the N.W. $\frac{1}{4}$ of section 28. The offset in the latter locality may be explained by folding, but the sharpness of the break in the former locality strongly suggests faulting. In any case, the extension and direction of the fault as indicated on the map is to a considerable degree hypothetical.

Knowledge of the structure of the northeast two-fifths of the Gwinn synclinorium pertains chiefly to the northeast limb. The most conspicuous structural feature of this limb is the broad cross-anticline responsible for the extraordinary surface exposure of the iron formation in the vicinity of the Austin and Stephenson mines, giving rise to two prominent synclines, the northern one carrying the Princeton No. 2 ore body and the southern one the Austin-Stephenson deposit (see cross-section I–II). Northward from Princeton No. 2 mine the east limb is overturned and dips at an angle of about 80° to the northeast, about parallel to a faulted contact with black slate extending from somewhere north of the Old Swanzy pit in the S.W. $\frac{1}{4}$ of the N.E. $\frac{1}{4}$ of section 18 southeast for a distance of probably more than a mile. Where observed in the Swanzy pit and in the Princeton No. 1 pit in the S.E. $\frac{1}{4}$ of section 18, the dip of the fault plane is northeast about 75° or 80°. Both the iron formation and the adjacent slate are intensely sheared along the zone of faulting. The belt of slates adjacent to the fault on the northeast may be stratigraphically either above or below the iron formation so far as the writer has proof. The upper and the lower slate members of the Gwinn series are lithologically very similar. Drill holes and the mine workings show that the iron formation in this vicinity lies directly on the basal arkose member of the Gwinn series with here and there a few feet of black slate lying between them. This makes it very probable that the slate belt northeast of the fault belongs to the upper slate member of


GEOLOGICAL MAP
OF THE
PRE-CAMBRIAN FORMATIO
OF THE
GWINN IRON BEARING DISTRICT OF MI
BASED ON RECORDS OF DRILL HOLES BY THE CL
CLIFFS IRON COMPANY AND THE OLIVER IRON M
AND FIELD MAPPING BY R.C.ALLEN. - 191
BY
R.C.ALLEN ASSISTED BY O.R.HAMILTON.
ESCANABA RIVER
CEMETERY
GWINN
NEW SWANZY
18
17
19
20
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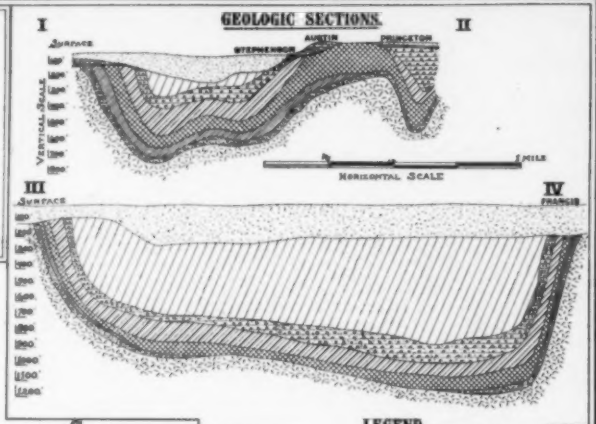
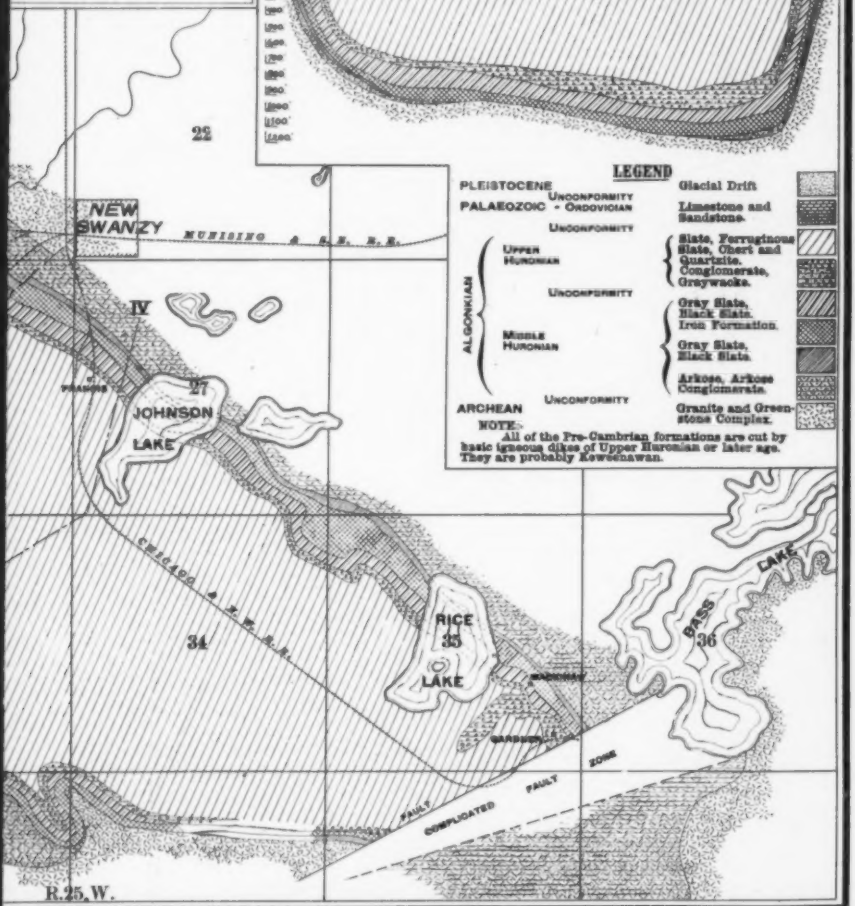
I
II
III
IV
T.43.N.
R.25.W.

# AL MAP
E
## FORMATIONS
E
STRICT OF MICHIGAN.

HOLES BY THE CLEVELAND
E OLIVER IRON MINING CO.
R.C.ALLEN. - 1913.

O.R.HAMILTON.




LEGEND

| | | |
|---|---|---|
| PLEISTOCENE | | Glacial Drift |
| | Unconformity | |
| PALAEOZOIC - ORDOVICIAN | | Limestone and Sandstone. |
| | Unconformity | |
| ALGONKIAN | Upper Huronian | Slate, Ferruginous Slate, Chert and Quartzite. Conglomerate, Graywacke. |
| | Unconformity | |
| | Middle Huronian | Gray Slate, Black Slate. Iron Formation. Gray Slate, Black Slate. Arkose, Arkose Conglomerate. |
| ARCHEAN | Unconformity | Granite and Greenstone Complex. |

NOTE.- All of the Pre-Cambrian formations are cut by basic igneous dikes of Upper Huronian or later age. They are probably Keweenawan.

the Gwinn series. North of the middle of section 18, details of the structure are unknown but the distribution of formations indicated by the few exposures and drill holes suggests deformation by both folding and faulting of a complex character.

### ARCHEAN SYSTEM

The Archean system comprises both acid and basic plutonic rocks, granite greatly predominating. These rocks inclose the synclinorium on the west, north, and east sides, encircling the north and northwest sides in bold hills and protruding through the drift in low knobs on the east side from New Swanzy northward. Numerous drill holes reach the system after penetrating the overlying sedimentaries within the borders of the synclinorium.

### ALGONKIAN SYSTEM

The Algonkian system is represented by two unconformable series of Huronian sedimentary rocks, the Princeton (upper) and the Gwinn (lower) series. Both series are intruded by basic dikes, probably of Keweenawan age. The basal conglomerate of the Gwinn series contains pebbles and bowlders of quartzite, quartz slate, and siliceous, cherty, slightly dolomitic slate derived from a third sedimentary series unconformably below the Gwinn series but not present so far as known in the Gwinn synclinorium.

### MIDDLE HURONIAN

#### GWINN SERIES

There are four members of the Gwinn series, viz., from the base upward, (1) conglomerate and arkose, (2) black slate and gray slate, (3) iron formation, and (4) black slate, gray slate, and graywacke.

1. *Conglomerate-arkose.*—The basal member of the Gwinn series is mainly arkose and arkose conglomerate. It lies on an uneven surface of Archean granite and is reported to occur in isolated patches over a considerable area outside of the Gwinn synclinorium. Within the fold its thickness varies from practically nothing to above 60 ft. The dominant phase of the member is arkose or decomposed granite. It is evident that the arkose has its origin

in the disintegration and subsequent sedimentation of the disintegrated particles of the underlying granite which in many places it resembles so closely that distinction is difficult. There are phases of the arkose in which the feldspar crystals show little perceptible wear, much less the quartz grains. It is particularly difficult to separate from granite in places near the contact where secondary mica has developed and veins of quartz and pegmatite occur like those in the granite. Phases in which there has been perceptible or conspicuous rounding of the quartz and feldspar particles are commonest and these may be either massive or schistose. The schistosity in the arkose is the result of mashing of the feldspars, by which process the quartz grains are generally not greatly affected. Where the arkose is overlain by the iron formation and particularly by iron ore, as in the mines north and west of Gwinn, it is in many places highly decomposed, soft, and iron stained, the feldspars being largely kaolinized.

The conglomerate is much less abundant than the arkose and according to drill records is not present in most localities. Its occurrence seems to be erratic and, curiously enough, where exposed in the S.E. $\frac{1}{4}$ of the S.W. $\frac{1}{4}$ of section 19, T. 45, R. 25, it lies some distance above the base of the formation. Drift bowlders of the conglomerate are rather plentiful but the only exposures known to the writer are in the S.W. $\frac{1}{4}$ of section 19. Here there are 12–15 ft. of it exposed in layers from 1 to 2 ft. thick dipping about 16° E. and striking N. 15° W. At this locality the contact with the granite is about 150 paces west. The matrix of the conglomerate is chiefly arkose but in one exposure it is siliceous, gray slate interbedded with the arkose. The pebbles are up to several inches in diameter and are mainly vein quartz which is abundant in the underlying granite. There are also many fragments of green schist, dense, vitreous, gray quartzite and siliceous, cherty, slightly dolomitic slate of grayish-green color. The composition of the conglomerate may also be studied to advantage on the waste dump of the Gwinn mine in the N.E. $\frac{1}{4}$ of the N.W. $\frac{1}{4}$ of section 28 where a bowlder bed was encountered in cutting the pumping-station in the shaft. All of the bowlders are well rounded and vary up to 6 to 7 inches in diameter. The matrix is arkose so decomposed that many

of the bowlders are lying free on the dump. In addition to the rocks represented in the exposures in section 19 there are many bowlders of granite and greenstone.

The origin of the quartzite and slate pebbles is of great interest in its bearing on the correlation of the Gwinn series. Near Little Lake, about five miles east, in a range of hills on the north side of section 19, T. 45, R. 24, there are numerous outcrops of quartzite, quartz slate, and arkose. Van Hise and Leith considered these rocks to be the base (Goodrich quartzite) of the Gwinn series which we have described. In fact, their description seems to apply mainly to these exposures and not to the basal member of the Gwinn series as it actually exists in the Gwinn synclinorium. There is an arkose and arkose conglomerate in these exposures exactly similar even to the pebbles in its associated conglomerate, to the basal member of the Gwinn series. This formation, however, is plainly uncomformably below the quartzites and quartz slates, as proven by the occurrence of a coarse conglomerate at the base of the quartzite carrying numerous bowlders of the arkose some of which are as much as 2 ft. in diameter. The exposures at Little Lake are not in the Gwinn synclinorium but will be described in a later paper. The point is emphasized, however, that the presence of quartzite and cherty, quartz-slate pebbles in the basal member of the Gwinn series proves that there is at least one unconformable series of sediments between the Archean and the Gwinn series. The writer believes that this series is the Lower Huronian as represented in the Marquette district a short distance north.

2. *The lower slate.*—In the southeastern three-fifths of the district a black, graphitic, and gray slate formation intervenes between the basal arkose member and the iron formation. It is less generally present from the Stephenson mine northward, in this area never exceeding a few feet in thickness, but south of the Stephenson mine it varies up to above 60 ft. thick. Were it not for lithologic dissimilarity this slate would be included in the basal member, but inasmuch as it represents a distinct change in conditions of sedimentation and moreover seems to maintain a definite stratigraphic relation to the overlying and underlying formations, it should perhaps be described as a distinct member of the series.

3. *The iron-bearing member.*—Like the other formations in the Gwinn series the iron-bearing member varies markedly in thickness but is nevertheless persistent, occupying a constant and definite stratigraphic position in the series. The description of the occurrence of this member in "lenses and layers" in slate by Van Hise and Leith is misleading in so far as this implies that the member is discontinuous within the synclinorium. The thickness of the iron formation is ordinarily 50–100 ft. with a maximum of probably less than 125 ft. and a minimum of only a few feet as shown in some drill holes toward the center of the basin west of the Princeton and Stegmiller mines. Some sections show a greater thickness than 125 ft., which is accounted for by folding. The formation is thinner and at the same time leaner toward the west side of the synclinorium. All of the known ore bodies are on the east limb of the fold.

The iron formation is mainly banded, ferruginous chert similar to the "soft ore jasper" of the other Michigan ranges. The original or unaltered phase is cherty iron carbonate. North of the Swanzy pit in section 18, the base of the formation, as shown by drilling, seems to be mainly grünerite schist. This part of the district shows evidence of greater deformation by folding and faulting than areas farther south.

The upper part of the iron-bearing member is slaty in many places and the base of the overlying slate is here and there so ferruginous that it is a matter of choice as to whether it should be mapped as slate or iron formation. On the map these phases are included in the overlying slates.

The iron ores are both Bessemer and non-Bessemer grades, the latter greatly predominating, very soft and fine textured in the main and generally high in moisture. A purplish satin luster is a peculiar characteristic of the Gwinn ores. There are some pits in the upper part of the formation west of the Austin mine that show hard jasper and hard, blue hematite. Localization of the ores is largely coincident with synclinal troughs and faulted zones but is not limited to these structures. An inclined position of the iron formation between the overlying slate and underlying slate or arkose satisfies the structural requirements for ore concentration.

4. *The upper slate.*—The upper slate member is from 30 to 100 ft. thick. It is unconformably overlain by the basal conglomerate of the Princeton series. Its relation to the underlying iron-bearing member is largely gradational. It comprises an interbedded series of black slate, gray slate, and dark graywacke-quartzite. The black graphitic phase is more commonly directly above the iron formation than the gray slate, and the graywacke-quartzite phase seems to be in upper and middle horizons.

PRINCETON SERIES

The Princeton series consists of an interbedded series of slates, ferruginous slates, and cherts, quartzites, ferruginous quartzites, and graywacke with a basal conglomerate. The series is 400–500 ft. thick. Probably the entire thickness is not represented in the Gwinn fold. It is rarely seen in outcrops but it has been penetrated by numerous drill holes and some open pits. For the purpose of this article the interesting member is the basal conglomerate.

The basal conglomerate varies from 30 to 50 ft. to more than 100 ft. in thickness. Nearly all of the many drill holes which cross its horizon show its presence but here and there it is represented by a coarse graywacke. So far as known, the only exposures are in the S.E. $\frac{1}{4}$ of the N.E. $\frac{1}{4}$ of section 18, T. 45, R. 25, where a number of exposures occur on a low brush-covered ridge. Adjacent to them on the east the upper slate member of the Gwinn series is exposed in pits. The strike of the conglomerate is N. 70° W. and the dip 80° N.

The matrix of the conglomerate is coarse, dark graywacke-quartzite, the pebbles are chert and siliceous black slate, quartz, and arkose, derived from the underlying Gwinn series, and quartzite. The matrix carries a good deal of disseminated ferruginous material and some very small fragments of iron ore. There are also a good many small irregular cavities in the rock which are lined with hematite and limonite produced by weathering-out of iron-bearing fragments of some kind. The largest chert fragments are two to three inches long and one-half to an inch wide. All of them show wear by attrition, the smaller ones being generally lens shaped.

So far as can be ascertained, the Princeton and Gwinn series are structurally almost accordant. The strike of the conglomerate

where exposed in section 18 indicates discordance in trend with the Gwinn series, but too little is known of the structure in that vicinity to place any importance on this observation.

### KEWEENAWAN SERIES (?)

Basic dikes have been cut in a few drill holes and may be observed in section 20, T. 45, R. 25, cutting the basal arkose member of the Gwinn series. These dikes intrude both the Princeton and the Gwinn series. They are younger than Palaeozoic and older than the Princeton series. Their age is therefore probably Keweenawan.

### PALEOZOIC

Isolated remnants of limestone and sandstone of Cambrian or Ordovician age, or possibly both, occur throughout the district. Some of these are in excess of 50 ft. thick. No fossils or other means of determining the exact age of these outliers is available at the present time.

### CORRELATION OF THE GWINN AND THE PRINCETON SERIES

It has been shown that the pre-Cambrian sedimentary rocks of the Gwinn synclinorium consist of two unconformable series. The unconformity between them is marked by a basal conglomerate the position, extent, and thickness of which imply an important erosion interval which intervened between the periods of deposition of the two series.

Concerning the respective ages of these two series, it may be said that probably no geologist familiar with the pre-Cambrian formations of the Lake Superior region would correlate the Gwinn (lower) series with the Lower Huronian. It contains an important iron formation associated with graphitic slates, an assemblage of rocks not known in the Lower Huronian. Moreover, the basal conglomerate carries fragments of quartzite and quartz slate dissimilar to any known Archean sediments in Michigan but exactly similar to certain Lower Huronian rocks in the adjacent Marquette district. This evidence considered in connection with the unconformity separating the Princeton and the Gwinn series is a sufficient basis for the correlation suggested in this paper, but an additional consideration tending to show that the Gwinn series is

Middle Huronian appears in the absence from its basal conglomerate of jasper fragments from the Negaunee formation so strongly developed in the adjacent Marquette district.

Escape from the correlations suggested in this paper involves a disregard or subordination of the importance of the unconformity separating the Gwinn and the Princeton series. There is no certain evidence in this synclinorium of great structural discordance between these two series but it may be and probably is as great as that separating the Upper Huronian and the Middle Huronian series of the Marquette district. Great structural discordance could hardly be expected inasmuch as the main deformation took place after the deposition of the Princeton series. Some structural discordance is implied in the consideration that although the upper slate member of the Gwinn series was probably not cut through in this district, there was sufficient erosion in adjacent territory to uncover the different members of the entire Gwinn series prior to the deposition of the basal conglomerate of the Princeton series.

# EVIDENCE OF THE MIDDLE-UPPER HURONIAN UNCONFORMITY IN THE QUARTZITE HILLS AT LITTLE LAKE, MICHIGAN

R. C. ALLEN AND L. P. BARRETT

A critical examination of the exposures of quartzite, quartz slate, and arkose in the hills near Little Lake in T. 45 N., R. 24 W., Marquette County, Michigan, was inspired by the results of recent studies by the senior writer in the Gwinn synclinorium, which lies between five and seven miles west.

The Gwinn synclinorium contains two series of Huronian sedimentary rocks, separated by an unconformity which is characterized by a conglomerate at the base of the upper (Princeton) series containing fragments derived from the various formations (including a productive iron-bearing member) of the lower (Gwinn) series and also from a third sedimentary series not represented in the synclinorium. The work at Little Lake resulted in the identification of an unconformity which, in connection with other data to be described, establishes a basis for correlation of the formations at Little Lake with certain of those in the Gwinn synclinorium.

So far as the writers are aware, no previous mapping and careful study of the rocks at Little Lake has been made. Rominger barely mentions the locality in 1894 in the statement that "iron-bearing rock beds occur in the vicinity of Little Lake."[1] Reference was again made to this locality in 1911 by Van Hise and Leith[2] who correlated the quartzite, quartz slate and arkose in the hills at Little Lake with the Goodrich quartzite or basal member of the Upper Huronian as developed in the Marquette district and the arkose and arkose conglomerate at the base of the Gwinn series in the adjacent Gwinn (Swanzy) synclinorium.

The succession and correlation of the formations in the Gwinn synclinorium and those at Little Lake are given below:

[1] *Michigan Geological Survey*, 1894, Vol. V, Part I, p. 71.

[2] C. R. Van Hise and C. K. Leith, *Monograph 52, U. S. G. S.*, pp. 283-86.

CORRELATION TABLES

GWINN SYNCLINORIUM AND LITTLE LAKE HILLS

| | Gwinn-Little Lake District, U.S. Geol. Survey, 1911. | Gwinn District, Mich. Geol. Survey, 1913. | Little Lake Hills, Michigan Geol. Survey, 1913. |
|---|---|---|---|
| Quaternary System | Pleistocene Series—Glacial Deposits. | Pleistocene Series—Glacial Deposits. | Pleistocene Series—Glacial Deposits. |
| Ordovician System? or Cambrian System? | Unconformity<br>Limestone<br>Sandstone | Unconformity<br>Limestone and sandstone | Unconformity<br>Limestone |
| Algonkian System—Keweenawan Series | Unconformity | Unconformity<br>Not identified but probably represented by basic dikes which intrude all of the pre-Cambrian formations. | |
| Huronian Series<br>Upper Huronian | Michigamme slate<br>Bijiki iron bearing member in lenses and layers near base of Michigamme slate.<br>Goodrich quartzite. Quartz slate and quartzite grading down into arkose or recomposed granite. | Michigamme slate, carrying beds of ferruginous slate and chert, quartzite, and graywacke.<br>Conglomerate and graywacke (Goodrich). | Quartz slate and quartzite<br>Conglomerate |
| Middle Huronian | | Unconformity<br>Iron-bearing formation and associated overlying and underlying slate (Negaunee-Siamo).<br>Arkose conglomerate, arkose and quartz slate conglomerate (Ajibik). | Unconformity<br>Conglomerate, arkose, and quartzite |
| Lower Huronian | | | |
| Archean System<br>Laurentian Series<br>Keewatin Series | Unconformity<br>Granite | Unconformity<br>Granite and greenstone, mainly granite | Not exposed near Little Lake Hills.<br>Probably granite |

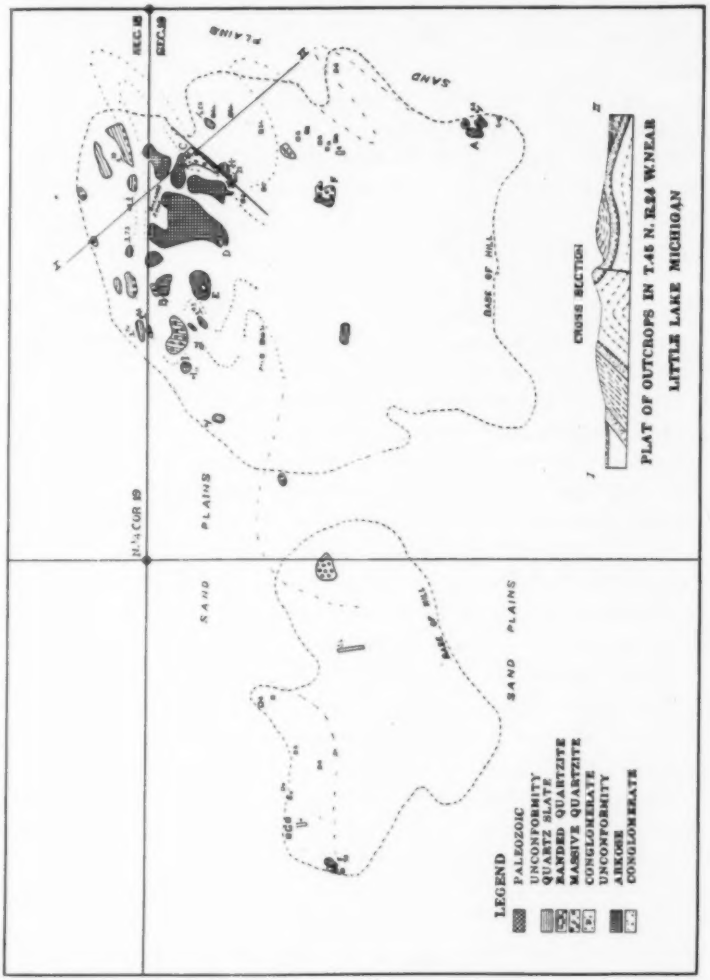
## STRUCTURE OF THE LITTLE LAKE HILLS

Rising to a height of possibly 100 feet above a featureless flat sand plain near the station of Little Lake are two hills on which there are many exposures of pre-Cambrian arkose, quartzite, and quartz slate with associated conglomerates. These hills present today, in reference to the fluvio-glacial sand plains in which their bases are buried, somewhat the same appearance that they seem to have had near the close of pre-Cambrian time, when they were monadnocks on a pre-Cambrian peneplain, for remnants of flat lying Paleozoic (Cambrian or Ordivician) limestone still cling to their sides and summits.

The eastern and larger hill is nearly a half-mile in diameter; the western and smaller one is about three-eighths of a mile long in an E.–W. direction with a basal width of about one-eighth of a mile. The exposures are most abundant on the north half of the east hill, but on both hills there are a large number of pits and trenches which were dug many years ago by prospectors whose diligence deserved a better reward than this locality seems to have offered. Aside from the red color of some of the quartz slate beds in the upper series, iron-stained shear zones in the quartzite and arkose, and an exposure at locality *F* (see figure) of about eighteen inches of hematite occupying a lens-shaped cavity along a zone of thrust faulting in massive quartzite, there appears no present evidence of the attractiveness which these hills seem to have presented to the early prospector for iron ore.

The structure of the north side of the east hill is apparently an anticline, the crest of which has been cut away by erosion, thus exposing the arkose and associated conglomerate of the lower (Gwinn) series flanked on the north, east, and west sides by conglomerate, quartzite, and quartz slate of the upper (Princeton) series. This is the only complete structural feature which can be determined from the available data. There is evidence in the development of cleavage and schistose structures, shear zones and faults of both normal and thrust type, that general deformation has been severe. Further evidence of the intensity of deformation is afforded in the overturning of the formations, with consequent apparent reversal in succession, in exposures at locality *A* at the

southeast extremity of the east hill. While evidence of minor faulting is abundant in outcrops and pits, it is found impossible




with information available to trace the course or measure the throw of any of these faults. The fault at locality *C-H* is a partial

exception but the only thing known about this fault is its direction and the fact that its vertical displacement is inconsiderable. In reference to the structure of the west hill perhaps no inferences are warranted. So far as known, the arkose of the lower series is not exposed but the distribution of the lower and higher members of the upper series together with the topographic expression faintly suggests a shallow syncline trending across the hill in a N.E.–S.W. direction carrying the quartz slate member in the trough and exposing the underlying quartzite on its opposite flanks. But the structure is probably not so simple as this for there is evidence of faulting in some of the pits.

### THE LOWER (GWINN) SERIES

*Arkose and conglomerate.*—The major portion of the arkose formation is in reality now an abundantly sericitic quartzite, the sericite being a metamorphic derivative of the original feldspar. The abundance of sericite affords on cleavage surfaces, a characteristic pearly luster. From the dominant phase there are gradations through intermediate phases to typical arkose with feldspar practically unaltered. Of subordinate importance are interstratified lenses of conglomerate varying from a foot or two up to eight feet in thickness. The pebbles are mainly vein quartz well rounded and of various sizes under four inches in diameter. Other pebbles of dense, vitreous, gray quartzite, black chert, and siliceous dolomitic slate are much less abundant. The matrix of the conglomerate beds has the composition of quartzite rather than arkose and is usually dark, dense, vitreous, and slightly sericitic.

Bedding structure is not observable in any of the various phases of the formation, except as it may be represented by an occasional thin layer of gray chert. The deposition of these cherty layers probably heralded the approach of a change in conditions of sedimentation represented by an iron-bearing member in the adjacent Gwinn synclinorium which lies in part directly on a similar arkose-conglomerate formation. At Little Lake the iron-bearing member appears to have been removed by erosion prior to the deposition of the overlying conglomerate and quartzites. The

similarity of the arkose-conglomerate of Little Lake to that at the base of the Gwinn series extends to the pebble content. Rounded fragments of dolomitic siliceous slate, and gray quartzite are common to both localities, but the bowlders of granite and green schist which occur in the conglomerate of the Gwinn district were not observed in the exposures at Little Lake.

### UPPER (PRINCETON) SERIES

The upper series, so far as represented at Little Lake, comprises a higher horizon of red- and gray-banded quartz slate and slaty quartzite grading down through banded quartzite and massive non-bedded quartzite into a basal conglomerate.

*Conglomerate.*—The contact of the upper and the lower series is exposed at localities *B* and *C* (see figure). At locality *B* this contact is distinguishable only on careful examination. The base of the upper series on weathered exposures is not conspicuously dissimilar to the underlying arkose except on freshly fractured surfaces which reveal, in contradistinction to the underlying sericitic, quartz-feldspar rock, a dense, hard matrix of quartzite holding pebbles of vein quartz of sizes less than an inch in diameter. At locality *C*, however, all doubt of the unconformable relations of the arkose-conglomerate and the overlying series is dispelled. The change from arkose to dense, black, vitreous quartzite is abrupt at a wavy contact of knife-like sharpness. In addition to the quartz pebbles observed at locality *C* there are pebbles of chert and large bowlders of the underlying arkose above one foot in diameter. The arkose bowlders are much softer than the embedding matrix of quartzite and weather out to form characteristic pit-like depressions. The full thickness of the basal conglomerate is not exposed at locality *C*, but at locality *B* it is apparently only six feet. At *C* only about four feet are observable.

*Quartzite and quartz slate.*—There are three distinct main phases of this series, viz., (1) a massive phase associated with the basal conglomerate, grading upward into (2) a banded phase which in turn is over-lain rather sharply by (3) beds of gray- and red-banded quartz slate. Although these three phases correspond to definite stratigraphic horizons, considerable difficulty is experienced in

correlating the various exposures of the different members of this series. The chief difficulties refer to the relation of the quartzite on the west hill to that exposed on the east hill and to the determination of the stratigraphic position of the two outcrops of quartzite north of the slate at the base of the east hill. The outcrops of gray quartz slate and red-banded quartz slate on the north slope of the west hill are apparently stratigraphically above the exposures of quartzite in outcrops and pits on its northwest and northeast sides. Whether the quartzite at the base of the north slope of the east hill is stratigraphically above the quartz slate or represents the underlying massive quartzite brought up by faulting cannot be determined.

Extended description of the different phases of the quartz rocks in the upper series has little interest for present purposes. The dissimilarities of the different members refer mainly to texture and bedding structures rather than to composition. The red color of certain layers in the quartz slates is caused by the presence of small particles of finely disseminated hematite.

*Notes on the correlation.*—In a former paper the senior writer discussed the importance of the unconformity separating the Princeton (upper) and Gwinn (lower) series in the Gwinn synclinorium and adduced evidence in support of the correlation of these two series with the Upper and Middle Huronian. The lithologic similarity of the arkose-conglomerate formation at Little Lake to the basal member of the Gwinn series, only a few miles distant, considered in connection with the unconformity separating it from the overlying quartzites and quartz slates is a sufficient basis for extending the arguments for the correlations in the Gwinn district to cover the two unconformable series at Little Lake. The geology of each area accounts for three unconformable series of sedimentary rocks corresponding to the Lower, Middle, and Upper Huronian of the adjacent Marquette district. The upper two series are present while the lower one is represented in both areas by fragments of some of its formations in the base of the middle series.

The absence in the lower series at Little Lake of the slate and iron formation members developed in the Gwinn synclinorium

strengthens the evidence of the importance of the erosion interval which intervened between the deposition of the Princeton and Gwinn series. Incidentally it has a practical bearing on the possibilities for success attendant on drilling for iron ore in the immediate vicinity of the Little Lake Hills. Some drilling, of which the writers have no records, has already been done and we understand that additional drilling is contemplated by parties who are likewise ignorant of the results of the former explorations.

# PHYSIOGRAPHIC RELATIONS OF SERPENTINE, WITH SPECIAL REFERENCE TO THE SERPENTINE STOCK OF STATEN ISLAND, N.Y.

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The serpentine highland of Staten Island is one of the most anomalous physiographic features of the Cretaceous peneplain of the Atlantic seaboard. This ancient and widespread base-level slopes southeastward and seaward from the highlands of Southern New York and Northern New Jersey; and from the latter district it has been designated, locally, the Schooley Plain. In its approach to the coast it is most continuously and perfectly preserved in the long, straight crest of the Palisade trap ridge. This approach is, in fact, unbroken to Kill Van Kull; and the peneplain passes below sea-level in the northwestern quarter of Staten Island. The normal seaward gradient of the peneplain, in the vicinity of the coast, as proved by numerous deep borings, ranges from 75 to 100 feet per mile; and nowhere else is it so perfect and so perfectly preserved as where it is still covered and protected by the Cretaceous sediments beneath which it was progressively buried as it slowly sank below sea-level, and in so sinking received its finishing touches in the addition of marine planation to terrestrial peneplanation.

Beneath the southeastern and southern plain or lowland of Staten Island, the peneplain, developed here on the Manhattan schists, has been found by the drill at depths (increasing seaward) of 200 to 400 feet, or just where its normal gradient would have led us to expect it. But between the northwestern and southeastern lowlands the continuity of the buried peneplain is interrupted by the great lenticular stock of serpentine nearly eight miles long from northeast to southwest and fully three miles in maximum breadth, and rising to an extreme height of nearly 400 feet above the sea, or 400 to fully 800 feet above the encircling peneplain. The southeastern slope, especially, of this relief is very abrupt and in part

almost precipitous, the boldness of the ridge being, in general, one of its most impressive aspects. It is noteworthy, also, that it consists entirely of serpentine and embraces the entire known area of the serpentine. The Manhattan schist on the southeast side of the ridge and the Triassic trap and sandstone on the northwest side, are wholly outside of the highland area, being strictly confined to the lowland or, rather, to the underlying peneplain, although the trap, at least is far more resistant than the serpentine.

The serpentine relief clearly holds the general or formal relation of a monadnock to the Cretaceous peneplain above which it towers;

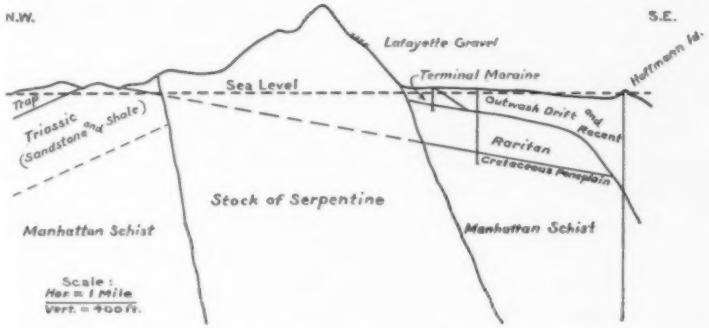


FIG. 1.—Cross-section of Staten Island, showing the geologic and topographic relations of the stock of serpentine.

and this most obvious interpretation of the Staten Island bedrock relief demands the first consideration. In this connection it may be noted that serpentine, owing to its insolubility and general chemical stability, imperviousness, massive structure, and tight joints offers greater resistance to erosion than its inferior hardness would indicate; and it is not improbable that in the relatively inert nature of the stone we have an adequate explanation of some of its topographic reliefs, especially where the surrounding formations are of a weak and yielding character. A general survey of serpentine occurrences, the world over, shows, however, that, almost regardless of the geologic environment, they are, if of a massive character (stocks, dikes, etc.), characterized by topographic relief.

Evidently, some other factor than differential erosion is required for a full and satisfactory explanation, especially in the case of such an ancient and pronounced serpentine relief as the Staten Island highland, standing, as it does, in close proximity to the coast and to the mouth of a large river. It is simply inconceivable that with its more complete exposure to the agents of erosion—subaerial, fluvial, and marine—the Staten Island serpentine stock should have been able successfully to resist erosion and maintain its high relief throughout the period during which the far harder and more resistant diabase of the nearby Palisade ridge was completely base-leveled.

The obvious inadequacy of the monadnock or residuary-relief explanation of the serpentine heights of Staten Island has led Willis and Dodge[1] to explain the relief of the serpentine by faulting. According to this explanation, Staten Island Heights would seem to stand as a solitary instance on our entire Atlantic seaboard of important post-Cretaceous faulting not due to glacial agency; and glacial drag and thrust must be powerless to elevate the bedrock *en masse*, especially at the extreme limit of the ice invasion. It is, however, further suggested by Willis and Dodge that this supposed faulting may be correlated with that traversing the Newark (Triassic) rocks of New Jersey; although it is commonly conceived that the faults of the Triassic strata date from Triassic time. Were they post-Cretaceous, they could not fail to break the continuity of the Cretaceous peneplain elsewhere than on Staten Island. The suggested faults would be rather unique, also, in closely circumscribing the serpentine area without traversing or breaking the inclosing schist or the Triassic sandstone and trap. Evidently, this explanation is not altogether satisfactory; and it appears advisable to seek further. In fact, we seem forced to the conclusion that the serpentine possesses an inherent power of growth or self-assertion that has enabled it, progressively, to lift its head above the base-level to which it may have been at least approximately reduced in Cretaceous time.

Assuming, as we must, that this great stock of massive and essentially structureless serpentine has been derived from some massive, basic, and highly magnesian igneous rock, such as peri-

[1] *U.S. Geol. Survey, Folio 83; Science*, February 20, 1903.

dotite, we find in the process of serpentinization and the consequent inevitable expansion the requisite innate power of growth and topographic rejuvenation. This alteration, of which hydration is now the most important phase, and which is simplest, most direct, and most important for the mineral olivine, involves in every case a notable diminution of density and increase of volume, the volumetric gain, according to Van Hise,[1] ranging, with different species and varying conditions, approximately from 15 to 40 per cent. It is, of course, to this notable expansion that we owe the tightness of the joints and the internal slickensides and slip-fiber veins so characteristic of massive serpentine.

Under the conditions surrounding an approximately vertical plug or stock, at a great depth in the earth, the expansion due to serpentinization cannot be, to any large extent, isometric (cubic), but must take place chiefly or wholly upward, that is, in the direction to give it the maximum topographic value. This means that for the maximum ratio of expansion, 40 per cent, and ignoring contemporaneous erosion, the surface exposure of the serpentine stock would be elevated nearly 40 feet for every 100 feet in depth of peridotite altered to serpentine; or one-half as much for an assumed mean expansion of 20 per cent. These relief or topographic values may, however, be exceeded in the cases, probably numerous, where the diameter of the stock increases downward, the sepentine then reaching the surface by accelerated flow through a more or less contracted vent.

If we assume, with Van Hise,[2] that serpentinization is limited to the zone of katamorphism, the estimated depths of which range from 30,000 to 40,000 feet, the total vertical expansion in this zone, even for the minimum ratio, would still account many times over for the relief of the pseudo-monadnock of Staten Island Heights—a monadnock developed, in the main at least, subsequently to the peneplanation and in a manner suggesting comparison, rather, with the growth of the spine of Mont Pelé.

We have here, apparently, a new physiographic type, a variety of auto-relief not heretofore clearly recognized; and comparison with the spine or obelisk (pelélith) of Mont Pelé is inevitable The pelélith, we may suppose, resulted from the extrusion (or protrusion)

[1] *U.S. Geol. Survey, Monograph 47.* [2] *Ibid.*

of a solid, and in the lower part merely a highly viscous, plug of lava by the vertical expansion of less viscous lava beneath, through the separation, due to cooling and relief of pressure, of aqueous and other vapors and various gases. The serpentine relief of Staten Island, on the other hand, is believed to be due to the extrusion (or protrusion) of a plug or stock of serpentine by the vertical expansion resulting from the progressive downward growth of the serpentine through the hydration and consequent swelling of the anhydrous magnesian rock in the alteration of which it has its origin. Reliefs formed after the manner of the Mont Pelé obelisk are now known as *pelēliths;* and parity of usage suggests *statenliths* as an appropriate designation for serpentine reliefs formed on the plan or after the manner of Staten Island Heights. It is, of course, conceivable that a rock formation, antecedent or subsequent, covering a serpentine stock may, by continued upward growth of the latter, be lifted into a dome; and such a dome, somewhat comparable with a laccolithic dome, may be called a statenlithic dome.

For proof that the statenlith of Staten Island is not unique, a solitary instance, we need look no farther than Castle Point, in Hoboken, between 7 and 8 miles north of Staten Island and approximately on the line of strike of the Staten Island serpentine stock. This point forms a hill about half a mile long and 100 feet high, consisting exclusively of serpentine. It holds the formal relation of a monadnock, not to the Cretaceous peneplain, but to the topographically lower Miocene base-level or partial peneplain very perfectly developed on the Manhattan schist and Triassic sandstone and shale of Hoboken and Jersey City. That this relatively small serpentine relief, standing on the very brink of the deep, buried gorge of the Hudson, post-dates the base-leveling of the inclosing formations is most probable. It is, thus, essentially similar in its geologic and physiographic relations to the Staten Island serpentine, a parallel instance, and unquestionably a true statenlith.

The question naturally arises at this point as to whether or not statenliths include only serpentine reliefs; and the answer must be that, on theoretic grounds, at least, various other secondary, hydrous silicates are entitled to recognition, notably the chlorites and probably talc. The chlorites are chiefly derived from augite, hornblende, and biotite; and the total expansion, including acces-

sory epidote, quartz, iron oxide, etc., ranges approximately, according to Van Hise,[1] from 10 to 25 per cent. We are not restricted here to bodies of pure or approximately pure chlorite, such as chlorite schist; but may properly take account, also, of the vastly more extensive chloritic rocks known collectively as greenstones —massive, basic, igneous rocks (diabase, diorite, gabbro, etc.)— which have, in the zone of katamorphism, undergone the greenstone alteration, of which chloritization is the principal phase. The outcrops of dikes, stocks, etc., of greenstone are commonly protuberant; and if more salient than the relatively resistant nature of the rock would lead us to expect, we may find in the expansion, of which the chloritization is a reliable index, an entirely adequate explanation. Furthermore, the differential movement resulting from the expansion is very generally attested by internal slickensides.

Again, if the question be raised as to whether statenliths are necessarily limited to silicate rocks, the answer, on theoretic grounds at least, must be in the negative; for the hydration of anhydrite to form gypsum involves, in the absence of solution, the very notable expansion of 60.3 per cent; and the resultant deformation, it is well known, may be very severe. Also, it is matter of common knowledge that gypsum, in spite of its extreme softness and ready solubility, is not infrequently characterized by decided relief, and may be classed as to some extent a hill-forming rock. Occurring mainly or normally as a sedimentary deposit, it must, however, lack the power of persistent topographic rejuvenation, save where the strata have exceptional thickness or are highly inclined.

The dynamic and structural relations of the statenliths to the various other types of relief are expressed in the following systematic outline:

OUTLINE OF A GENETIC CLASSIFICATION OF RELIEFS

Superficial Agencies
- Destruction (erosion) reliefs
  - Youth = continuous, lobate plateaus
  - Maturity = connected, dendritic ridges
  - Senility = isolated hills—monadnocks

[1] *U.S. Geol. Survey, Monograph 47.*

Construction (accretion) reliefs
Littoral and fluvial = spits, bars, deltas
Eolian = dunes
Glacial = drumlins, moraines, eskers, kames
Subterranean Agencies
Construction (accretion) reliefs
Igneous extrusion = volcanoes and peléliths
Igneous intrusion = laccoliths and laccolithic domes
Aqueous extrusion = tufa cones and terraces
Aqueous intrusion = crystosphenes and saline domes[1]
Deformation reliefs
Plication = anticlinal and monoclinal ridges, domes and plateaus
Dislocation = block mountains and plateaus
Hydration and vertical swelling = statenliths and statenlithic domes

Serpentine is a rock of rather restricted distribution. In Eastern North America it is chiefly confined to the narrow and discontinuous Appalachian belt of peridotite and other basic magnesian rocks (to the alteration of which the serpentine owes its origin) in the western margin of the seaboard zone of crystalline rocks (igneous and metamorphic). In this belt, extending from Newfoundland and Gaspé Peninsula to Central Alabama, the basic magnesian rocks tend to occur in a series of isolated lenses (lenticular stocks and dikes) the axes of which coincide with the strike of the enclosing gneiss and schist.[2] The Staten Island and Hoboken stocks of serpentine are thus seen to be entirely typical in their structural relations; and it is a legitimate inference from these that all of the stocks in which serpentinization is well advanced are, theoretically at least, statenliths. Many of the serpentine stocks exhibit actual relief, notwithstanding the resistant nature of the inclosing formations; but rarely, probably, is the relief so marked or so sharply defined as in the type example.

[1] A crystosphene, as defined by Tyrell (*Journal of Geology*, XII, 232–36), is a lens of ice formed in or beneath the tundra of high latitudes and arching up or doming the overlying materials. It is here proposed to broaden the definition to include the saline domes of the Gulf Coastal Plain and, in general, all instances where the surface has been domed by mineral (ice, salt, sulphur, gypsum, etc.) segregation and crystallization. This appears permissible, since crystosphene may equally well be translated ice-wedge or crystal-wedge.

[2] *North Carolina Geological Survey*, Vol. I, Plate 4.

In Central Alabama the basic magnesian and serpentine belt passes beneath the Coastal Plain and the conditions become favorable to the occurrence of statenlithic domes. It is interesting, therefore, to find directly on this line 90 miles and 120 miles respectively, from the border, the Lower Peach Tree anticline and the Hatchetigbee anticline, the one intersected by the Alabama River and the other by the Tombigbee River. These deformations of the Coastal Plain sediments are essentially unique east of the Mississippi. That they are normal folds, due to horizontal compressive stress, is sufficiently improbable to suggest that they may be either saline domes or statenlithic domes; and it is hoped that the testimony of the drill will decide the matter in the near future.

Although these anticlines have marked geologic relief, the upward arching of the Eocene, and, presumably, of the Cretaceous strata amounting to hundreds of feet, they are devoid of topographic relief, the Pliocene (Lafayette) strata crossing them without deviation. In other words, they were base-leveled in Pliocene time and have suffered no subsequent deformation, the power of growth, whatever its source, seeming to be quiescent or exhausted. A further distinct indication that they are not true statenlithic domes is found in the fact that their axes, trending with the strike of the Coastal Plain formations, are directly transverse to the course of the basic magnesian or serpentine belt.

It appears, then, that an unquestionable statenlithic dome remains to be identified; although it may be suggested in passing that in so far as the saline domes are due to the derivation *in situ* of gypsum from anhydrite they belong to this new type of relief.

The contact of the statenlith with the bordering formations is a true fault; and to this extent Willis and Dodge are right in their interpretation of Staten Island geology. But they err, as I believe, in correlating the obvious displacement with ordinary fracture and slip faults and with the extended, rectilinear displacements of the Triassic strata. The latter originated in a profound crustal readjustment involving the entire depth of the katamorphic zone and tapping, in some cases, reservoirs of the most truly abyssal magmas. The statenlith displacement, on the other hand, strictly

limited to the periphery of the serpentine stock and to the katamorphic zone, finds its origin in the quiet and unobtrusive chemical reactions of that zone involved in the secular absorption and downward penetration of meteoric water, and the displacement must, obviously, die out downward.

Apparently, then, we have in the statenlith not only a new physiographic type, but also, in its periphery, a hitherto unrecognized type of fault, a type finding its origin in the localized, deep-seated expansion, through hydration, of the base of the upthrow block. Assuming that the horizontal dimensions of the statenlith increase downward, the encircling fault would be, structurally at least, of the normal or gravity type.

Pursuing this subject a step further, and recognizing that reversed or thrust faults are due to horizontal compression, that normal or gravity faults are due to vertical compression, and that vertical compression can yield only normal faults, we may, on genetic grounds, distinguish two types of normal faults: first, those due to the gravitative settling of the hanging wall block; and, second, those due to the upward expansion of the footwall block. The expansion of the footwall may be, in varying proportions, both thermal and aqueous, that is, due to the absorption of heat and of water, the normal fault of this type being the precise geologic concomitant of the statenlith.

On passing now to the consideration of the relations of the Staten Island statenlith to the history of the Coastal Plain, of which it is one of the most commanding relief features, we are confronted at the outset with the question as to whether or not the statenlith's innate power of topographic rejuvenation has enabled it to keep its head above water throughout Cretaceous and Tertiary times, thus making it a perpetual watch tower guarding the mouth of the Hudson. Although continuity of relief through geologic ages, a sort of physiographic immortality, is conceivable, it is, nevertheless, highly improbable. The clearest disproof of topographic perpetuity would, of course, be afforded by overlying Coastal Plain sediments; but this evidence, unfortunately, is almost wholly wanting; although its absence proves nothing to the contrary.

The only sediment referable to the Coastal Plain series now resting upon the Staten Island serpentine is the yellow gravel

(Lafayette) scantily preserved on a bench or terrace above the steep southeast slope of the serpentine ridge, at elevations of 180 to 220 feet above the sea. Since this gravel is identical in character with the Lafayette (Beacon Hill) of New Jersey, and the elevation is that normal for the Lafayette in the latitude of Staten Island, this correlation appears inevitable; although it involves the conclusion that the elevation of the marginal part of the serpentine, relatively to the Cretaceous peneplain, has remained unchanged since Pliocene time; with the further suggestion that the central and higher part of the serpentine (180 to 360+ feet) has experienced a differential elevation of nearly 200 feet in post-Pliocene time. An alternative but not very probable view is that the serpentine was not completely base-leveled in Pliocene time. That the central part of the stock should rise most rapidly or should continue to rise after the elevation of the periphery has virtually ceased is not difficult to understand, especially if the stock becomes larger downward, since in that case serpentinization of the central part may be conceived as lagging behind the serpentinization of the peripheral part.

As the surface of the ground is lowered by erosion, the lower limit of the zone of katamorphism and of serpentinization must be correspondingly depressed; although it is probable that the latter effect tends to lag behind the former. Downward extension of serpentinization means a 15 to 40 per cent or greater upward extension of the summit of the serpentine, the topographic relief of the serpentine being, thus, constantly renewed and increased. It is probable, however, that when erosion was sufficiently long continued with reference to a definite base-level, as during the Jurassic and early Cretaceous subaerial peneplanation and marine planation of the site of Staten Island, the process of serpentinization, overtaking the slowly receding and finally stationary lower limit of the zone of katamorphism, was, for the time being, virtually exhausted. The upward growth of the serpentine then ceased; and it was, at least approximately, base levelled with the surrounding formations, and, in due course, covered by the conformable series of Upper Cretaceous and Eocene sediments.

The marked elevation and consequent extensive erosion of the land in early Miocene, substantially repeated in early Pliocene time, probably depressed the lower limit of the zone of katamorphism

and thus renewed serpentinization and the topographic relief of the serpentine stock. The meager data do not permit a more detailed or definite statement; but the best general conclusion appears to be that throughout the Coastal Plain history the downward extension of serpentinization and upward extension of the serpentine stock have been active during periods of elevation and rapid erosion and quiescent during periods of base-leveling and sedimentation; and that, in spite of the present strong relief of the serpentine, developed in large part, presumably, during the great Pleistocene elevation, the successive Coastal Plain formations have been, in general, deposited across the serpentine area.

The uniformity and virtual continuity of the narrow Appalachian belt of basic magnesian stocks and possible statenliths suggests uniformity of age or practical synchronism, the indicated age being, roughly, Mid-Paleozoic, and the argument being approximately as cogent as for the Triassic age of the similarly homogeneous belt of basic eruptive and irruptive rocks associated with the sediments of that formation. The purpose now, however, is not to insist upon the precise age of the stocks of peridotite and allied rocks of the ultra basic magnesian belt, but, rather, to point out that in spite of similarity of composition, structure, and age, they present strong contrasts in the degree or extent of serpentinization and hence, presumably, of the statenlithic development.

Recognizing that the process of serpentinization (and the same is true of chloritization) belongs, in the zone of katamorphism, not to the superficial and shallow belt of weathering, but to the deeper and vastly more extensive belt of cementation, we realize that climatic conditions must be eliminated as possible factors in the differentiation of the stocks. Hence the fact that in the northern half of the ultra-basic magnesian belt serpentinization is, superficially at least, more general, and, as a rule, more complete than in the southern half, is without climatic significance. The meaning of this contrast, which is to a large degree regional, is not readily apparent. But, whatever the initial cause of serpentinization, even though we tacitly assume its beginning, in any case, as essentially fortuitous or accidental, once begun this becomes a determining cause of its continuance; and the change spreads through the mass as a veritable mineral contagion.

Of more special interest now, however, is the fact that in Western North Carolina and elsewhere stocks of peridotite and of other rocks susceptible of the serpentine alteration are unaltered at least near the surface. This suggests that when the serpentinization of these masses begins, if not already begun, in the deep zone of cementation, the resultant statenlith must be, for a time, crowned with the unaltered peridotite or other original rock. We should, therefore, be prepared to recognize serpentine statenliths where no serpentine is exposed to observation. The relief of certain stocks of peridotite in Western North Carolina has been attributed to the supposed superior resistance to erosion of the peridotite as compared with the inclosing gneiss; but it is here suggested that deep-seated serpentinization, attested by peripheral slickensides, is an explanation worthy of some consideration.

# THE MODE OF FORMATION OF CERTAIN GNEISSES IN THE HIGHLANDS OF NEW JERSEY

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## PART I. OBSERVATION OF FIELD PHENOMENA

In Northwestern New Jersey a broad belt of pre-Cambrian crystalline rocks extends across the state and is prolonged northeasterly into New York, forming there the Highlands of the Hudson. On the southwestern side it is continued into Pennsylvania. The rocks which compose this belt are of considerable variety. Gneissic rocks of several types predominate, but beds of crystalline limestone are associated with them, and masses of rock of granitic and dioritic character, showing at times almost no foliation, are also present. The general trend is northeast and southwest, with steep dips, usually toward the southeast.

The geological character of the region as a whole and of various portions of it has been frequently described. As in other areas of similar foliated gneisses in various parts of the world, the question of origin of the various types has been a most puzzling one. Certain observers have held them to be highly metamorphosed sediments; others have favored the view that they represent the partial differentiation of a still fluid magma, which by continued movement has pressed out the differentiated portions into broad sheets; and a third view would attribute their structure to the shearing and recrystallization of an already solidified mass.

In a number of visits which the writer has made to various portions of the area, certain features have been observed in several places which were believed to be of considerable significance in the interpretation of the mode of origin of the rocks in which they occurred, and during the past summer (1913) especially favorable conditions for observation were found at a quarry which is being newly opened up at Pompton Junction. The quarrying operations

and the stripping-off of the soil from a large area have disclosed the structural features in a very plain manner, and the relations thus revealed afford evidence toward an explanation of the processes by which the structures of the rock in question have originated. In this article it is proposed to give some description of the features found in this locality and to present the evidence regarding the mode of origin which they suggest. It has seemed desirable also to consider certain of the general properties of magmas with the purpose of finding an explanation for some of the phenomena observed in the field. It is believed that rock-types of a similar character are to be found in other portions of the area and indicate a similar origin, but at the same time it is recognized that the region as a whole is most complex and that this description and explanation do not apply to all parts of it.

In recent publications of the United States Geological Survey, W. S. Bayley and A. C. Spencer[1] have described in somewhat general terms certain features of the gneisses in a manner which indicates that a theory of origin similar in some respects to that which will be presented here was held in view, and others[2] appear to have favored similar explanations. Thus far, however, descriptions of the mode of action of the processes concerned, as illustrated by the resultant rock structures, and a discussion of the conditions under which they operated, appear to be lacking.

The quarry in question is that of the Pompton Pink Granite Company,[3] and is situated at the intersection of the New York, Susquehanna & Western Railroad and the Greenwood Lake Branch of the Erie Railroad, near the southeastern front of the Highlands.

A number of years ago a quarry was in operation at this point and a considerable amount of granite for building-purposes was obtained from it. The dressed stone was of a very pleasing appearance and was quite widely used, but difficulty was found in obtaining

[1] W. S. Bayley and A. C. Spencer, *Franklin Furnace Folio* (1908), and *Passaic Folio* (1908).

[2] J. V. Lewis, *Annual Report of the State Geologist of New Jersey for 1908*, p. 64.

[3] I wish to express my appreciation of the courtesy of the general manager of the company, Mr. Charles H. McIntyre, for the opportunity which was afforded to visit the quarry workings and all parts of the property.

large blocks free from streaks and bands of dark-colored minerals. This objectionable feature probably led to the abandonment of the workings. Recently another company has taken hold of the property and without attempting to do much work at the old site they have gone several hundred feet up the ridge, at the base of which the old quarry lies, and have exposed great masses of granite of the same composition as before, nearly free from inclusions. Extensive operations are now being undertaken at this point.

FIG. 1

In the *Annual Report of the State Geologist of New Jersey for 1908*, in an article on the building-stones of the state, J. V. Lewis gives an excellent description of the macroscopic and microscopic characteristics of the rock and some information regarding the field relations. It is evident that he recognized the intrusive nature of the granite into the gneisses of the region, but he does not enter into any extended description of the details and results of the process.

At the quarry itself and in the immediate vicinity two rock types are found, differing greatly from each other structurally.

The first is a very coarse-grained granite, almost a pegmatite in texture, in which crystals of microcline, or crystalline aggregates of the same mineral, occasionally attain a diameter of four or five inches. Where found in the largest masses it is almost free from dark minerals and consists essentially of quartz and two kinds of feldspar. In such places it is very massive and shows little or no indication of parallelism in the disposition of its constituent minerals. At the other extreme from this type is a finely banded

FIG. 2

gneiss, such as is shown in Fig. 1. This photograph was taken at an exposure of a large surface of glaciated rock about one-fourth mile (0.4 kilometer) north of the quarry, and the relations shown are typical of much of the rock in the vicinity. The light bands consist principally of quartz and feldspar, while the dark bands and streaks are characterized especially by large amounts of biotite, hornblende, or chlorite mixed with the quartz and feldspar. When developed in the manner shown in this photograph, either the dark or the light bands may individually have any thickness up

to several inches, and show remarkable continuity and parallelism. The relations shown at this point, however, are by no means universal. It is found frequently that the lighter bands swell and pinch in an irregular manner and that the darker bands are interrupted or fade out in places and may be continued after an interval. By a further development of such features and by an increasing predominance of the light-colored bands, we arrive at such results

FIG. 3

as are shown in Figs. 2 and 3. These views show another portion of the glaciated surface at the same locality as Fig. 1 and represent dark bands separated by the light-colored granitic rock and bordered on both sides by large masses of granite. These two photographs illustrate very well the persistence and continuity sometimes shown by the bands of basic rock through masses of granite, and also the manner in which they may suddenly lose their identity and fade out within a few feet or inches. Fig. 4 is a sketch of the details at the termination of one of the bands of Fig. 3. Fig. 5 shows somewhat similar features.

Microscopic examination of thin sections of the various types shows that the purest granite is made up almost entirely of microcline (having always a little microperthitic intergrowth) an acid plagioclase very near albite, and quartz. In such a type dark minerals may be almost lacking but when present they consist of aggregates of chlorite and epidote whose character bears evidence of a derivation from original biotite. Indications of a slight amount

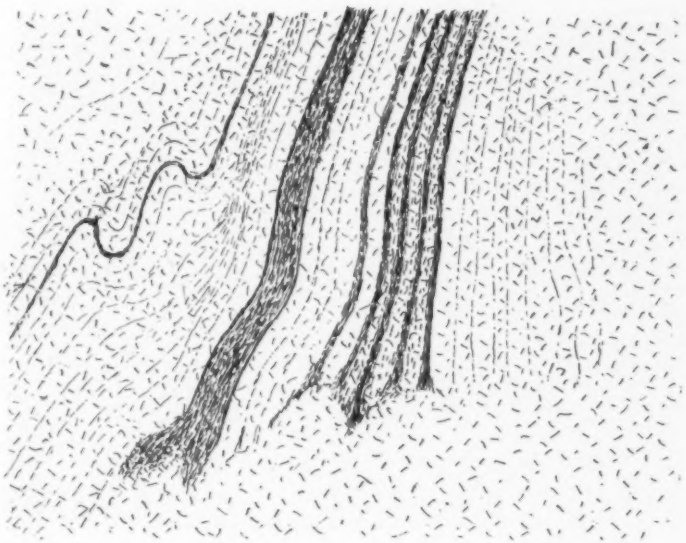

FIG. 4

of deformation are often shown by strain shadows in the quartz and the curving of twinning lamellae in the feldspars, and in some cases this has gone so far as to produce cracks, along which epidote, chlorite, quartz, and calcite have been deposited. It is very evident, however, that nothing resembling granulation or mashing has occurred. In the darker bands the distinctive feature is the large amount of biotite or hornblende present. In addition quartz is an important constituent, as well as microcline and acid plagioclase. Magnetite is also quite common, together with such secondary products as chlorite, epidote, and sericite in rather minor

amount. As in the massive granite, some indications of strain and deformation are apparent, but evidences of granulation to any important degree are lacking.

At the old quarry and at natural exposures in the neighborhood the rock masses exhibit features similar to those which have been described. Fig. 6 shows a portion of a glaciated surface adjacent to the old workings. The bands appearing in the foreground are

FIG. 5

composed of very dark hornblende-biotite gneiss, having a collective width of 2–3 feet, which are exposed for a length of about 25 feet and are cut off at both ends by granite. At their terminations the individual layers become considerably separated by an increase in the width of the dividing bands of granite. This is a feature which was noted in a number of instances. At each side there are large masses of coarse granite in which traces of dark minerals arranged in parallel lines are just visible.

In the old quarry, where dark inclusions are fairly plentiful, the quarry-faces, which are still perfectly fresh and clean, exhibit the

finer details of the relations between the granite and the basic streaks more plainly than do natural surfaces. Figs. 7–11 represent such exposures. In the vicinity of the quarries the coarsely granitic material is far in excess of the banded rock, but occasionally the latter is very plentiful, especially in the older opening. In places there is probably as much of the finely foliated rock as of the massive material; in other places there are great masses of granite

FIG. 6

almost free from inclusions (Fig. 12). Between these two extremes there are all degrees of transition in relative proportions of the two. Quite frequently the contact between granite and inclusions is sharp, although the minerals at the border always interlock; elsewhere the minerals characteristic of the inclusion become more and more infrequent at the sides until only faint parallel lines can be seen in the granite. The manner of transition shows several interesting features. It appears in some cases that the basic minerals at the immediate contact have become involved in the granitic magma without losing their identity or parallelism, so that a perfect

transition is produced from the hornblendic or biotitic gneiss or schist, in which foliation is prominent, through gradations in which the dark minerals become less and less noticeable and the proportion of granite increases, up to a type in which little or no parallelism of structure can be perceived. In other places

FIG. 7

the dark minerals appear to have been taken up or digested by the magma and to have crystallized out again in large blades. Even in the latter case it is not always certain that perfect solution has been effected at any one time. The process may have been rather in the nature of a chemical reaction with the original minerals or the solution and redeposition of a portion of the material at a time, leaving the general relations undisturbed. This possibility is

suggested by the fact that frequently even the coarser micaceous blades or aggregates of dark minerals show evidence of parallelism, and this would be difficult to account for under the supposition that solution was so perfect that the original structure was completely wiped out. In Fig. 9 some of these features may be seen. The band of dark inclusions appearing in the middle of the quarry-face has a boundary with the granite on the left-hand side which is

FIG. 8

quite sharply defined and persistent. On the right there is more scattering of the dark minerals and an irregular, ill-defined marginal portion. Still farther to the right the original bands have been pretty well replaced by coarse granite and show only as scarcely traceable lines of coarse mica or chlorite. The block shown in Fig. 11 would by itself be considered a fairly normal massive granite, but even here a suggestion of parallel arrangement of the dark minerals may be perceived, surviving as a slight evidence of the process by which it has been produced. Frequently, however, in the largest masses of granite all indications of a parallel structure are absent.

It was observed in many instances that in such occurrences as show bands of basic rock in largest amount the adjacent granite contains the greatest quantity of dark silicates, and where inclusions are rare the granite is very light colored and nearly free from ferromagnesian minerals, and it seems probable that the invading magma was composed essentially of quartz and feldspars, and that the dark minerals, even in massive

FIG. 9

granite, were derived to a large degree from the rocks which were invaded.

In the foliated gneisses the light bands are frequently of the same composition and appearance as the granite of the large masses, and their relations to such bodies and their general characteristics are such as to point strongly to their being essentially portions of the same magma which have traveled long distances along parallel layers of inclosing rock. The mechanism of injection appears to have involved a progressive movement of a rather thin magma between the layers of a foliated rock, in some cases spreading them

apart by the force of injection, elsewhere being transfused into the original layers and crystallizing these, or digesting and carrying away certain constituents, or entering into reactions with the component minerals. The variations found may be readily explained by the greater predominance of one or the other of these factors. The manner of action will be considered in more detail in Part II of this article. The fluidity of the magma is manifested

FIG. 10

by the narrowness and persistence of some of the injected layers. The question of the actual degree of fluidity will also be considered in the later discussion.

Certain phenomena suggest that a force of crystallization may at times have been an effective factor in separating the layers. Aggregates of microcline and quartz crystals in the form of augen are seen, inclosed by curving bands of schist as in Fig. 13. Such augen may have suffered a small amount of deformation and granulation of the solid material by shearing movements subsequent to crystallization, but obviously not to such a degree as to

drag out the crushed fragments into a band, as has occurred in some augen-gneisses.

Inasmuch as quarrying operations have exposed the rock masses in three dimensions, it is possible to arrive at a very clear conception of the form of the gneissic inclusions. It is seen that they dip very steeply and have an extension in depth comparable to their prolongation along the strike. Their form is therefore that of thinly tabular sheets.

FIG. 11

In general the strike of the bands is almost straight and conforms to the general northeast-southwest strike of the region, but in places the layers are more or less curved and occasionally so much contorted as to suggest a "kneading" of the material. In Fig. 10 one of the abrupt bends which are often visible is depicted. The movements in the magma by which such features were produced may perhaps be ascribed to the antagonism of forces brought into play by the up-welling of liquid magma into strata subjected to a tangential compression due to the weight of overlying rock. In all

cases, however, the appearance of the contorted strata was such as to imply that the flexures were of a minor order, not involving large masses of rock but suggesting considerable freedom of movement among the component layers. The contortions appear to have originated during the period of injection and not during subsequent movements of solidified rock. Frequently individual bands are sharply bent, while others lying at either side, but separated by intervening granite, are nearly straight. An instance

FIG. 12

of this may be seen in Fig. 3. On the whole the general parallelism of the basic bands lying in the midst of masses of granite and the agreement of their strike with the general strike of the region was a noticeable feature and was considered important in its implication regarding the mechanism of the process by which the granite was injected. It implies that the granitic magma entered among the layers of a previously schistose or foliated rock without causing great disturbance in their position. Some of the layers appear to have become incorporated in the magma, others were forced

apart and even sharply contorted in minor folds, but brecciation, or large disturbances of any sort appear to have been lacking. Where the invading magma entered in large quantity, movements of considerable amount within its mass appear to have occurred. One body having a width of nearly 200 feet was observed, in which the infrequent inclusions had a somewhat more blocklike form than in general and a variable strike, approaching at times a right angle to that which generally prevails, implying differential movements within this large mass of liquid. The dark bands shown in Fig. 14 lie somewhat to the northeast of this main mass of granite and trend directly toward it, and are bordered on either side by tongues or offshoots from it. As they approach the granite mass in their prolongation beyond the lower left-hand side of the photograph

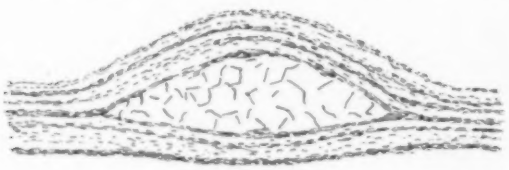

FIG. 13

they curve much more toward the left and are finally cut off or dissolved by the granite.

In the process of igneous intrusion illustrated at this locality it is quite certain that nothing in the nature of "stoping" was a factor of importance. It is not intended to imply, however, that such a process may not have been the effective means of intrusion in other instances. It is assuredly true that in different localities and under varying conditions the mechanics of intrusion have been radically unlike.

Several of the features which have been described argue against the probability that the dark bands represent squeezed-out differentiates in a mass of magma. Probably the most impressive evidence in this connection is the sudden termination of certain sharply defined bands, with indications of corrosion at the end, which was frequently observed. The same phenomenon is opposed to the idea that the elongated structure of the bands of schist is

essentially due to a plastic flow. Certain features of rupturing likewise suggest that the attributes of a rigid body were retained to some degree in such cases. Elsewhere, however, the phenomena are more consistent with the idea of softening. The abrupt flexures and general appearance of kneading of the material, as well as the manner in which certain bands gradually fade out along the strike, imply a partial fusion of the original material or a pene-

FIG. 14

tration of the magmatic liquor among the grains to such a degree that their mutual adhesion was diminished and some freedom of movement thus permitted.

There can be little doubt that during the period of intrusion the masses of rock now exposed were buried within the crust of the earth to a depth at which the increase of temperature due to the rise of the geotherms was considerable. In seeking an explanation of the phenomena of intrusion the question arises whether the conception which Sederholm[1] has advocated to account for the relations

[1] J. J. Sederholm, *Bulletin de la Commis. Géol. de Finlande No. 23* (1907).

observed in certain areas of pre-Cambrian rocks of Fenno-Scandia may be applicable. He urges that in certain cases the strata have been buried to such a depth that the rocks as a whole have become plastic, and the more fusible portions have actually formed a magma at the horizon observed or at a comparatively small depth below. We are hardly warranted from the evidence at hand in accepting this explanation here. The general parallelism and straightness of the bands indicate that prior to the injection of magma the dominant characteristic of the rock was fissility rather than plasticity. The phenomena of softening must therefore be attributed to the injection itself, but the evidence shows that while the magma was still in movement softening had ensued, and we are led to conclude that the process of injection was long continued. It appears, however, that in the New Jersey Highlands large areas show evidences of granitic injection of the type which has been described, suggesting that beneath such areas the conditions necessary for the softening and flow of masses of rock may have been realized.

The process by which the granite and gneisses have assumed the relations described in the foregoing pages appears to be similar in many respects to that which French geologists, notably Michel-Lévy and Lacroix,[1] have termed *lit-par-lit* injection. In their typical examples the phenomena are attendant upon the intrusion of batholiths of igneous rock into areas of Paleozoic sediments, and the contact phenomena may be plainly seen. In the New Jersey example the appearances imply rather the presence of a reservoir of magma at some lower level, from which offshoots in large and small apophyses were injected into the roof and are now exposed for observation. In many respects, however, the mode of injection appears so similar that the same term may be applied.

It will readily be seen that the resultant gneisses are believed to be composite rocks, made up of material of different sorts, derived from different sources. An older, sheared or bedded rock is postulated, to which magmatic material has been contributed; first, by

[1] The publications of these two authors which bear upon the subject are quite numerous. Special mention may be made of Michel-Lévy's *Bull. No. 36, Carte géol. fran.* (1893), and Lacroix's *Bull. No. 64* (1898) and *Bull. No. 71* (1900), *Carte géol. fran.*

injection along parallel layers, and second, by a process of absorption exerted by the original rock upon the injected magma. The latter process will be discussed a little later.

The nature of the original rock does not appear at all certain. The laminated character might as well be considered as representing bedding planes in a sedimentary series or shear planes in a schist of either sedimentary or igneous origin. The prevalence of ferromagnesian minerals in many of the bands might be supposed to imply a derivation from a basic igneous rock, but there is a question as to how far the present composition represents that of the original material. The French geologists mentioned have directed special attention to the profound changes wrought in the composition of the original sediments by "imbibition" of material derived from the igneous mass. Sederholm also has described similar phenomena accompanying the process of granitization, and the work of Adams and Barlow[1] in the Haliburton and Bancroft areas of Ontario is of great importance in this connection. The last-named geologists present evidence of the metamorphism over large areas of the pure, non-magnesian limestones of the Hastings-Grenville series into amphibolites and pyroxene-gneisses by transfusion of material from invading batholiths of granite.

There is some evidence not far distant from the quarries described that not all of the original rocks of the region could have been of a basic igneous character. About two miles ($3\frac{1}{4}$ kilometers) to the north, a little west of the railway station at Haskell, a bed of crystalline limestone or dolomite occurs in the gneissic series. The thickness is somewhat uncertain but appears to be 20 feet or more. In places the amount of carbonate minerals is large, though tremolite, phlogopite, and a pale-green pyroxene are extensively developed, as well as secondary serpentine. Elsewhere along the same belt carbonates appear to be wholly absent and the rock consists almost entirely of the greenish pyroxene or a mixture of pyroxene and quartz. The belt can be traced by occasional outcrops for several hundred feet. In one place a gneiss composed of feldspar, quartz, biotite, and much garnet occupies a

[1] Adams and Barlow, "Geology of the Haliburton and Bancroft Areas," *Memoir No. 6, Canadian Geological Survey* (1910); see especially pp. 87 and 157.

position either on the strike of the limestone or closely adjacent. The strike of the limestone bed is parallel to that of the associated gneisses—an indication that part at least of the foliation is to be attributed to an original bedding. The manner in which minerals from the magma may have been introduced into the limestone and other sedimentary beds will be considered in the discussion which follows.

[*To be continued*]

# THE MISSISSIPPIAN ROCKS OF NORTHEASTERN OKLAHOMA[1]

L. C. SNIDER
Norman, Oklahoma

At a recent conference of the state geologists of the states of the Mississippi Valley it was decided to have prepared a brief tabular statement showing the present state of knowledge of the Mississippian rocks in each state, for use of those interested. This tabular statement for Oklahoma has been prepared by the writer. However, such a table is necessarily greatly condensed, and this paper has been prepared to give a somewhat more detailed statement of our present knowledge of these rocks.

The brief outline presented herewith is the result of a rather thorough examination of the literature on the region, and of about five months of field work by the writer, assisted by J. B. Newby. The field work has not been completed, and there are still several points of stratigraphy and correlation on which definite statements cannot be made. The paleontological collections have been studied in only a preliminary way and the faunal lists are necessarily incomplete.

## LOCATION AND AREA

The Mississippian area in Northeastern Oklahoma is the southwestward extension of the Ozark Uplift of Missouri and Arkansas. It occupies the extreme northeastern part of the state, including all of Delaware and parts of Ottawa, Craig, Mayes, Wagoner, Cherokee, Adair, and Sequoyah counties. Portions of the Wyandotte, Vinita, Pryor, Siloam Springs, Tahlequah, and Muskogee quadrangles of the United States Geological Survey are included in the area. The region considered, and the relative position of the quadrangles are shown in the sketch map (Fig. 1). The Tahlequah and Muskogee quadrangles were surveyed by Joseph A. Taff for the United States Geological Survey, and the folios

[1] By permission of the Director of the Oklahoma Geological Survey.

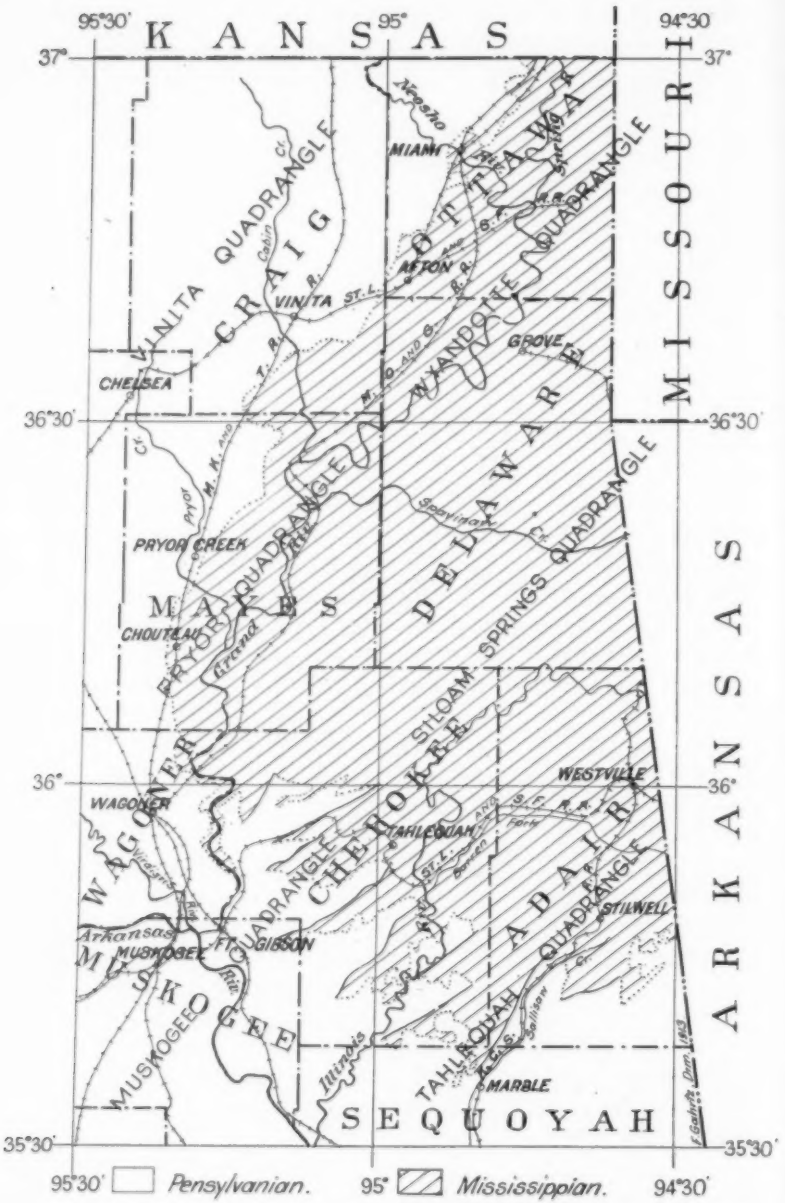


FIG. 1.—Sketch map of a portion of Northeastern Oklahoma showing the Mississippian area.

published several years ago. The Wyandotte quadrangle was surveyed by C. E. Siebenthal in 1907, and the Vinita quadrangle by D. W. Ohern in 1909, but the folios have not been published. The references to the geology of the Tahlequah and Muskogee quadrangles are to be attributed to the folios (Nos. 122 and 132 respectively) of the *Geologic Atlas of the United States*, prepared by Joseph A. Taff. It is not thought necessary to give footnotes for the individual references.

## STRATIGRAPHY AND PALEONTOLOGY

The Mississippian rocks of Northeastern Oklahoma comprise the following formations named from the base up: Boone formation, unnamed limestone, Fayetteville shale, and Pitkin limestone. The stratigraphy of all these formations varies considerably as the outcrops are followed west from the Arkansas line along the south side of the area and then north along the west side.

*Boone formation.*—The Boone formation covers by far the greater part of the area under consideration. In the Tahlequah and Siloam Springs quadrangles some of the deeper valleys are cut through the Boone into the underlying Devonian, Silurian, and Ordovician rocks, but the outcrops of these rocks are narrow and the Boone covers all the area indicated, except a comparatively narrow belt around the margin, which is occupied by the younger formations, and the outliers of these formations.

The Boone consists principally of limestone and chert, with a total thickness of from 100 to 350 feet. At or near the base of the formation there is locally a limestone member of up to 30 feet or even more in thickness. The upper part of this limestone is free from chert, thick-bedded, light-colored, and crinoidal. Near the Arkansas line, in the Tahlequah quadrangle, the limestone is locally absent so that the cherts rest directly on the Chattanooga shale. In no place in this quadrangle is the limestone reported as being over 15 feet in thickness. This thickness is exceeded in the Siloam Springs quadrangle, and the limestone is continuous to the northwest so far as observed. In the northern part of the area there are several feet of shaly limestone and flaggy limestone below the thick, crinoidal ledge which in this region is 10 to 15 feet thick.

This lower limestone member is correlated with the St. Joe limestone (marble) member of the Boone formation in Arkansas. It is well exposed in the Siloam Springs quadrangle along the Illinois River and some of its tributaries, along Spavinaw Creek in the Siloam Springs and Pryor quadrangles, and along the larger tributaries of Grand (Neosho) River in the Vinita and Wyandotte quadrangles. From collections made along the Illinois River in the Siloam Springs quadrangle, the following brachiopods have been identified: *Rhipidomella michelinia* L'Eveille, *Chonetes logani* N. and P., *Productus fernglenensis* Weller, *P. sampsoni* Weller, *P. sp.*, *Spirifer grimesi* Hall, *S. vernonensis* Swallow, *S. fernglenensis* Weller, *S. choteauensis* Weller, *Spiriferina subtexta* White, *Cyrtina burlingtonensis* Rowley, *Reticularia pseudolineata* Hall (?), *Cleiothyris royssi* L'Eveille (?), *Athyris lamellosa* L'Eveille, and *Ptychospira sexplicata* W. and W. The remainder of the fauna has not been studied, but the corals and some of the bryozoa appear to be identical with those described by Weller[1] from the Fern Glen formation, and which occur in the lower beds described in the next paragraph.

Locally there are darker-colored limestones with greenish shales below the St. Joe member. Taff describes these as occurring in one outcrop near the northern border of the Tahlequah quadrangle, where they have a thickness of 6 feet. A few miles to the north in the Siloam Springs quadrangle these same dark-colored limestones and green shales reach a thickness of about 40 feet, but they vary greatly in thickness in very short distances. The fauna of these rocks shows them to be equivalent to the Fern Glen formation of Missouri. To the northwest these rocks thin rapidly and in the northeastern part of the Pryor quadrangle along Spavinaw Creek, and in the southeastern part of the Vinita quadrangle along Big Cabin Creek there is only a layer of soft green clay shale, less than a foot thick, between the Chattanooga shale, and the St. Joe member of the Boone. Although no fossils have been found in this shale layer, it is believed to represent the Fern Glen on account of its character and position.

[1] Stuart Weller "Kinderhook Faunal Studies," V, The Fauna of the Fern Glen Formation, *Bull. G. S. A.* XX, 265–332.

The following species have been identified from the Fern Glen horizon in the Siloam Springs quadrangle: *Cyathaxonia arcuata* Weller, *C. minor* Weller, *Cladochonus americanus* Weller, *Amplexus brevis* Weller, *Fistulipora fernglenensis* Weller, *Cystodictya cf. lineata* Ulrich, *Actinocrinus rubra* Weller, *Rhipidomella michelinia* L'Eveille, *Schizophoria swallovi* Hall, *Productus fernglenensis* Weller, *P. sampsoni* Weller, *P. sp.*, *Camarotoechia persinuata* Winchell, *Spirifer vernonensis* Swallow, *S. fernglenensis* Weller, *S. grimesi* Hall, *S. choteauensis* Weller, *Spiriferina subtexta* White, *Athyris lamellosa* L'Eveille, *Cleiothyris prouti* Swallow, *C. royssi* L'Eveille, and *Platyceras paralius* W. and W. There are also several unidentified species of bryozoa, principally fenestellids. The *Productus* listed as *P. sp.* is a large species known to occur also in the Chouteau limestone of Missouri.

The greater portion of the Boone consists of limestone and chert. In most of the good exposures observed by the writer, the limestone and chert occur in alternate layers averaging about one to two feet in thickness. In many cases, however, the chert is distributed irregularly through the limestone as lenses and nodules. The cherts are often fossiliferous but practically no work has been done on the paleontology of the Boone in Oklahoma. In the Muskogee and Tahlequah folios Taff lists the following species from the cherts in the upper part of the formation: *Amplexus fragilis* White and St. John, *Glyptopora keyserlingi* Prout, *Fenestella multispinosa* Ulrich, *Polypora maccoyana* Ulrich, *Hemitrypa proutana* Ulrich, *Pinnatopora striata* Ulrich, *Spirifer logani* Hall, *Reticularia pseudolineata* Hall, *Productus setigerus* Hall, *Derbya keokuk* Hall, and *Capulus equilaterus* Hall. In a small collection from a few miles east of the town of Pryor Creek in the Pryor quadrangle the writer has noted *Productus setigerus*, *Spirifer logani*, and *Derbya keokuk*. This fauna is decidedly indicative of Keokuk age.

In general it may be said that there are no strata in the Boone in Oklahoma which permit the formation to be divided into members. In the Joplin district in Missouri, Siebenthal[1] distinguishes the Grand Falls chert and Short Creek oolite members. In the

[1] C. E. Siebenthal, Joplin District folio (No. 148), *Geologic Atlas of the United States, U.S. Geol. Survey*, 1907.

paper on the Mineral Resources of Northeastern Oklahoma[1] the same author describes the Short Creek oolite as being present in the eastern half of the Wyandotte quadrangle but does not mention the Grand Falls chert member. The extension of these members to the southwest is problematic.

As has been said the fauna of the Boone indicates the great mass of it to be of Burlington-Keokuk age. It has been reported[2] to the writer that fossils suggestive of Warsaw age have been found above the Short Creek oolite in Missouri. No collections from this horizon in Oklahoma have been studied and the exact age of the upper beds of the Boone formation in the State must be considered an open question as yet.

*Unnamed limestone.*—The upper limit of the Boone formation is one of unconformity. If the upper part of the cherts of the Boone are of Keokuk age, the time interval represented by the unconformity includes all of Warsaw, Salem, St. Louis, and Ste. Genevieve time. It is possible that more detailed work in the Boone area may prove some of the lower of these formations to be present, but so far as is known now they are absent.

Immediately above the cherts of the Boone in the Tahlequah quadrangle come a few feet of limestone which in this quadrangle were mapped with the Boone. In the Muskogee quadrangle, this limestone was found to be somewhat thicker and to be separated, at least locally, from the Boone by a thin layer of shale. The fossils proved the shale and limestone to be of Chester age, so they were considered as part of the overlying Fayetteville shale. North from the Muskogee, through the Pryor quadrangle this limestone thickens very rapidly until it attains a thickness of 90 or 100 feet along Grand (Neosho) River east of Choteau and Pryor Creek. In the Pryor quadrangle these rocks can be easily mapped and must be regarded as a formation. In view of the fact that this formation has been studied in the Vinita quadrangle, and that it will probably be named in the reports of the United States Geological Survey, no name is proposed here. This formation includes all the rocks between the Boone chert and the typical

[1] *Bull. U. S. Geol. Survey No. 340.*

[2] Personal communication from H. A. Buehler.

black clay shale of the Fayetteville shale. The correlation of these rocks to the north of the Pryor quadrangle is yet in doubt. They seem to keep the same general characteristics across the corner of the Vinita quadrangle that they have in the Pryor. In the Wyandotte quadrangle, however, there is considerable sandstone in the lower part of the Fayetteville shale, or below it, which Siebenthal[1] calls the Batesville sandstone. On a sketch map of the Pryor quadrangle sent the writer he uses the field term, sub-Batesville limestone, and it is understood that the same term was used in the Wyandotte quadrangle. Since the Batesville sandstone of Arkansas does not extend into Oklahoma on the south side of the uplift, it does not seem that the name can be used in the Wyandotte quadrangle, although the sandstone there occupies practically the same stratigraphic position as the typical Batesville. Siebenthal's sub-Batesville limestone is almost certainly the northward continuation of the unnamed Chester limestone formation of this paper, and the sandstone called Batesville may also belong to it.

The fauna of these limestones between the Boone and Fayetteville formations, so far as the collections have been studied, is as follows: *Productella hirsutiformis* Walcott, *Productus pileiformis* McChesney, *P. cestriensis* Worthen, *P. inflatus var. coloradoensis* Girty (?), *Liorhynchus carboniferum* Girty, *Camarotoechia purduei* Girty, *Moorefieldella eurekensis* Walcott, *Spirifer increbescens* Hall, *Reticularia setigera* Hall, *Seminula subquadrata* Hall, *Derbya keokuk* Hall, *Eumetria marcyi* Shumard, and *Deltopecten batesvillensis* Weller. There are also several species of bryozoa in the upper part and of pelecypods in the lower part of the formation that have not yet been identified. One layer of arenaceous and calcareous shale near the base is marked by a large trilobite. The fauna has, however, been determined with sufficient completeness to correlate these limestones with some degree of certainty with the Spring Creek limestone and the Moorefield shale and possibly with the Batesville sandstone of Arkansas.

The unconformity between this limestone and the underlying Boone chert has already been noticed. In the Tahlequah and

[1]C. E. Siebenthal, "Mineral Resources of Northeastern Oklahoma," *Bull. U.S. Geol. Survey No. 340*, p. 190, 1908.

Muskogee quadrangles this unconformity is not very striking as is shown by the mapping of the Chester limestone in the Tahlequah with the underlying Boone and by its separation from the Boone in the Muskogee only on account of the fauna and the thin layer of shale at the base of the limestone. In the Pryor quadrangle, however, this unconformity is very pronounced and the hills of typical Boone chert protrude through the limestone in several places, and in at least one place (hill just east of the town of Pryor Creek) through a considerable portion of the Fayetteville shale. The tops of some of the hills of Boone chert are at approximately the same level as the tops of other hills in the vicinity which are capped by the Pitkin limestone. The conditions are represented

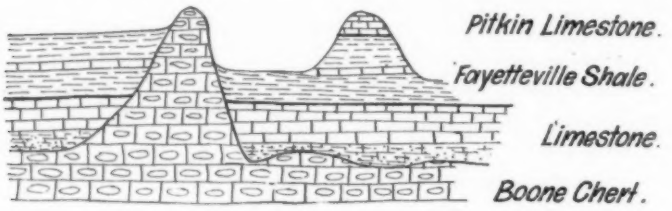


FIG. 2.—Diagram illustrating unconformity at top of Boone formation in the Pryor quadrangle.

diagrammatically in Fig. 2. When these hills were first observed they were thought to be structural domes but more careful work has shown that the limestones and Fayetteville shale lie up against the chert in a horizontal position so that the presence of a pronounced unconformity seems to be the only hypothesis which accounts for the hills of chert above the level of the unnamed limestone and the Fayetteville.

*Fayetteville shale.*—Near the Arkansas line in the Tahlequah quadrangle the Fayetteville shale is reported as reaching a thickness of 120 feet, but in the Muskogee quadrangle it is said by Taff not to exceed 60 feet. In a section measured southeast of Ft. Gibson by Ohern and the writer, however, the Fayetteville shows a thickness of about 100 feet. The formation consists principally of blue to black, fissile clay shales with thin limestones, usually lenticular. In the Tahlequah quadrangle there is a sandstone

member, the Wedington, which reaches a thickness of 40 feet. It thins out to the west and disappears about the middle of the quadrangle. In the Pryor quadrangle, the Fayetteville has the same general characteristics as to the south in the Muskogee quadrangle. The limestones thicken somewhat to the north, and are more persistent while the formation as a whole thins considerably. On the bluff of Grand River southeast of Choteau, the thickness is 90 feet. The basal 18 feet are composed of alternating layers of black shale and blue, dense limestone averaging about 6 inches in thickness. The limestone has a conchoidal fracture, is non-fossiliferous and weathers to a very light gray color. About the middle of the formation is a bed of limestone 12 feet thick, of which some layers are composed in large part of the shells of *Productus pileiformis* and *P. cestriensis*. This limestone is persistent for some miles to the north. So great a thickness has not been observed elsewhere, but this may be due to the poorer exposures.

The following species were collected from the limestones of the Fayetteville about 4 miles southeast of Ft. Gibson in the Muskogee quadrangle: *Lingulidiscina sp.*, *Productella cf. hirsutiformis* Walcott, *Productus sp.*, *P. pileiformis* McChesney, *P. cestriensis* Worthen, *P. cf. inflatus var. coloradoensis* Girty(?), *P. cf. subsulcatus* Girty, *Moorefieldella eurekensis* Walcott, *Spirifer arkansanus* Girty, *S. increbescens* Hall, *Martinia glabra* Martin(?), *Spiriferina sp.*, *Camarophoria sp.*, *Reticularia setigera* Hall, *Seminula subquadrata* Hall, and *Eumetria marcyi* Shumard. The following additional species are listed by Taff in the Muskogee folio: *Septopora cestriensis* Prout, *Archimedes compactus* Ulrich, *A. communis* Ulrich, *A. intermedius* Ulrich, *A. swallovanus* Hall, *Polypora corticosa* Ulrich, *Spiriferina spinosa* N. and P.

To the north, in the southeastern corner of the Vinita quadrangle, it is necessary to consider the Fayetteville and Pitkin horizons together. The section of the Mississippian rocks above the Boone chert in this vicinity is made up of four limestones and three shales. The lowest limestone is the unnamed limestone at the top of the Boone which has been considered. The topmost limestone is about 15 feet thick, and is probably the Pitkin limestone, although there is some doubt as to this correlation. The

other two limestones are thin, not over 5 feet in thickness. They and the shale between them are very fossiliferous, bryozoa being especially abundant. Exceptionally well-preserved shells of *Productus*, and *Chonetes* as well as screws of *Archimedes* and specimens of other bryozoa weather from the shale in abundance. The *Productus* is the species which is doubtfully identified with *P. inflatus var. coloradoensis* Girty, in previous lists in this paper. The *Chonetes* is a rather large, flat species which is apparently unnamed. Specimens of the same species from Arkansas are in the University of Chicago collection.

In addition to these forms the following species have been identified from the two lower limestones: *Lioclema gracillimum* Ulrich, *Fenestella cestriensis* Ulrich, *F. serratula* Ulrich, *Streblotrypa nicklesi* Ulrich, *S. distincta* Ulrich, *S. major* Ulrich, *Stenopora tuberculata* Prout, *Polypora cestriensis* Ulrich, *Pinnatopora vinei* Ulrich(?), *Pinnatopora sp.*, *Cystodictya nitida* Ulrich, *C. cf. lineata* Ulrich, *Thamniscus furcillatus* Ulrich, *Productus cestriensis* Worthen, *Spirifer increbescens* Hall, and *Spiriferina transversa* McChesney.

*Pitkin limestone.*—In the Tahlequah quadrangle the Pitkin limestone varies in thickness from about 5 feet to 70 feet. In character it varies from an impure, shaly limestone to a massive blue, crystalline limestone. In the Muskogee quadrangle the thickness of the Pitkin varies little from 50 feet. The formation in this quadrangle consists of light blue to brown, granular, earthy, slightly oolitic strata interbedded with fine textured massive layers. The individual beds vary from thin, platy layers, often separated by thin shale partings, to massive layers 2 feet in thickness. In this quadrangle the Pitkin is apparently perfectly conformable above the Fayetteville and below the Morrow formation of Pennsylvanian age. Indeed, the line between the Pitkin and the Morrow is very difficult to follow, and the separation is usually made on the basis of fossils. From the Muskogee quadrangle north, the Pitkin thins very rapidly and also changes in physical characteristics. The massive, pure limestone phase disappears and the formation becomes argillaceous and ferruginous. Locally the limestone is very sandy. In these localities the beds are thick, and on weathering show intricate cross bedding. Where there

is little sand in the formation the limestone is thin bedded and platy. The surfaces of the thin plates are usually covered by fossils in a more or less weathered condition; bryozoa are particularly abundant but are commonly poorly preserved.

The thickness of the Pitkin in the Pryor quadrangle is seldom over 20 feet and is usually less. From the middle of the quadrangle northward the Pitkin is locally absent, and the sandstones of the Pennsylvanian lie upon the shale of the Fayetteville, or in some places, upon the limestone about the middle of that formation. In such cases the basal portion of the Pennsylvanian sandstone is conglomeratic, containing pebbles of limestone up to an inch or more in diameter. The Mississippian-Pennsylvanian unconformity is thus very noticeable in the Pryor quadrangle, although it is not evident in the quadrangle to the southward. As noted in a previous paragraph, the correlation of the Pitkin in the Vinita quadrangle is in doubt. The topmost of the four limestones in this vicinity is probably the Pitkin. In the paper previously mentioned Siebenthal refers to the Pitkin as being present in the Wyandotte quadrangle, but gives no details concerning it. The section, however, is known to be very similar to that of the Vinita quadrangle.

The fauna of the Pitkin is very similar to that of the limestones of the Fayetteville. *Archimedes* is very abundant and the limestone was called the Archimedes limestone in the older reports of the Arkansas survey. The bryozoa which occur so abundantly in the formation in the Pryor quadrangle have not been studied as yet. The fauna is undoubtedly very similar to that already listed from the Chester limestones in the Vinita quadrangle, which may be in part from the Pitkin horizon.

## SUMMARY

The Mississippian area in Northeastern Oklahoma is continuous with the Ozark region of Missouri and Arkansas. The section includes the Boone formation, unnamed limestone of Chester age, Fayetteville shale, and Pitkin limestone. The Boone formation and chert is from 100 to 350 feet thick and ranges in age from Kinderhook to Keokuk. The Kinderhook is represented by shale

and limestone occurring locally at the base of the formation which are correlated with the Fern Glen formation of Missouri and Illinois. The great portion of the Boone is of Burlington-Keokuk age. The Warsaw, Salem, and Ste. Genevieve are supposed to be absent, the formations above the Boone being of Chester age. At the base of the Chester is a formation consisting principally of limestone which is very thin along the southern part of the area, but thickens to at least 100 feet along the western side, where the unconformity between it and the Boone is very marked. The Fayetteville shale thins from the Arkansas line westward and northward. The sandstone member (Wedington) disappears and limestones become more important. The Pitkin limestone thickens and becomes more regular in thickness westward from the Arkansas line into the Muskogee quadrangle, and then thins rapidly and becomes argillaceous and ferruginous to the northward. In the Pryor and Vinita quadrangles it was locally removed by erosion before the deposition of the overlying Pennsylvanian rocks.

It should be repeated that the work on these rocks is still in progress and that this paper is merely a statement of the facts concerning them so far as they are known at present. The faunal lists given are admittedly very incomplete, their aim being to list only the better known or more abundant species.

## *PETROLOGICAL ABSTRACTS AND REVIEWS*

EDITED BY ALBERT JOHANNSEN

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RAMSAY, WILHELM. "Ueber die Verbreitung von Nephelinsyenitgeschieben und die Ausbreitung des nordeuropäischen Inlandseises im nördlichen Russland," *Fennia*, XXXIII (1912), No. 1, pp. 17.

On the Kola Peninsula the high mountains of Umptek and Lujavr-Urt consist of nephelite syenite. Other nephelite rocks occur in the foothills of Turja and probably in the neighborhood of Kuollejavr. The author gives a sketch map of the region over which fragments of these rocks have been distributed by glacial ice.

A. J.

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REINISCH, REINHOLD. *Petrographisches Praktikum, II Teil, Gesteine*. Gebrüder Borntraeger, Berlin, 1912. Pp. viii+217, figs. 48. M. 7.60.

In this, the second edition, the same general mode of treatment has been followed as in the first. The book has been increased in size by the addition of 37 pages and 26 figures, even though the chapter on the chemical relationships of the igneous rocks has been omitted. The parts dealing with eruptive and metamorphic rocks have been rewritten entirely and numerous analyses have been added. The origin of the rocks is not touched upon, the work dealing simply with the rocks themselves and their determination under the microscope. They are described both megascopically and microscopically, and their metamorphism and weathering is discussed. Not only are chemical analyses given, but each analysis is also recalculated according to the Osann system. The book is strongly bound in linen, the press work is good, and the illustrations, which are unusually good line drawings, are clean and sharp. The addition of a diagram showing the relationship between the different rock types would have been a help to beginners, since for such the book is intended.

ALBERT JOHANNSEN

RIES, HEINRICH. *Building Stones and Clay Products.* John Wiley & Sons, New York, 1912, 8vo, pp. xvii+415, figs. 20, pls. 59. $3.00 net.

A handbook for architects. In Part I the important building stones of the United States are discussed with regard to their desirability as structural material, and with brief petrographic descriptions.

Part II opens with a chapter on the properties of clay, following which the clay products used as structural material are taken up and discussed, chiefly in their technologic aspects.

The principal interest to the geologist is found in the rather complete catalogue of quarries, with brief description of the stone obtained and lists of various structures in which these stones have been used.

The work is not intended as an exhaustive treatise, but aims to give mply the fundamentally important facts, and in this it seems to be fairly successful. ALBERT D. BROKAW

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RINNE, F. "Baueritisierung, ein kristallographischer Abbau dunkler Glimmer," *Berichten d. math.-phys. Kl. kgl. sächs. Gesell. d. Wiss., Leipzig*, LXIII (1911), 441–45.

The author proposes the name Bauerite for bleached biotite, and Baueritization for the process of bleaching. A. J.

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SCHALLER, WALDEMAR T. "New Manganese Phosphates from the Gem Tourmaline Field of Southern California," *Jour. Wash. Acad. Sci.*, II (1912), 143–45.

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SCHALLER, WALDEMAR T. *Beitrag zur Kenntnis der Turmalingruppe.* Inaug. Diss. München. Leipzig, 1912. Pp. 343.

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SCRIVENOR, JOHN BROOKE. "The Gopeng Beds of Kinta (Federated Malay States)," *Quar. Jour. Geol. Soc.*, London, No. 270, Vol. LXVIII (1912), 140–63.

In this interesting article the author gives a geologic and petrographic description of the Gopeng beds, and advocates the theory that they were formed as a result of glacial action. These beds, which are described as resembling "drift composed of till and bowlder-clays," are found overlying strata of Carboniferous age and are considered older than an associated Mesozoic granite. The Gopeng beds carry commercially valuable deposits of tin which is found for the most part as disseminated

grains of cassiterite. In his conclusion the author presents a brief summary of the geologic history of the region about Gopeng.

HEATH M. ROBINSON

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SKEATS, E. W., and SUMMERS, H. S. "The Geology and Petrology of the Macedon District," *Bull. Geol. Surv. Victoria*. Victoria, 1912. Pp. 58, map, and pls. 28.

The granodiorite of this region is shown to be intruded into the dacite, and an altered zone was found in the dacite at its contact with the granite. Two new rock types, macedonite and woodenite, are described. They somewhat resemble orthoclase basalts and have some characters in common with mugearites. A number of rocks previously determined by Professor Gregory are here redescribed. Twenty-nine analyses of igneous rocks are given and computed in the Cross, Iddings, Pirsson, Washington system.

A. J.

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SKEATS, ERNEST W. "The Occurrence of Nepheline in Phonolite Dykes at Omeo," *Australasian Asso. Adv. Sci.*, XIII (1912), 126–31.

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STEWART, CHARLES A. "The Geology and Ore-Deposits of the Silverbell Mining District, Arizona," *Bull. 65, Amer. Inst. Min. Eng.*, 1912, 455–505.

Among the igneous rocks described are alaskite, alaskite porphyry, biotite granite, quartz porphyry, andesite, rhyolite porphyry, hornblende andesite porphyry, and an almost pure quartz rock.

A. J.

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TYRRELL, G. W. "The Late Palaeozoic Alkaline Igneous Rocks of the West of Scotland," *Geol. Mag.*, IX (1912), 69–80, 120–31.

The writer divides the late Palaeozoic intrusive rocks of the west of Scotland into three groups, those with conspicuous analcite, those with conspicuous nephelite, and those without conspicuous analcite or nephelite, but which may contain either or both as accessories. Among the first class he describes analcite-syenite, teschenite, picrite-teschenite, lugarite, and monchiquite. Lugarite resembles the heronite of Coleman, and is related to leucocratic teschenites and to ijolites. It occurs in the form of a sill 4 feet thick in the Lugar teschenite-picrite complex, and as dikes penetrating the picrite. In hand specimens it shows a grey or greenish-grey groundmass crowded with barkevicite prisms up to

3 inches in length, and smaller black augites. In thin section the rock is seen to be composed of analcite, nephelite, plagioclase (probably $Ab_1An_1$), barkevicite, titanaugite, ilmenite, and apatite. The rock may be regarded as an ijolite in which the greater part of the nephelite has been displaced by original analcite, and in which barkevicite is a prominent constituent as well as augite.

The rocks of the second class are theralite, essexite, and kylite. The latter rock consists of about 31 per cent labradorite, 4 per cent nephelite, 1.3 per cent, analcite, 26 per cent titanaugite, 32 per cent olivine, 3.3 per cent ilmenite, 1.7 per cent biotite, 0.7 per cent apatite. Megascopically it is compact, fresh, phanerocrystalline, rather fine grained, and of a grey or greenish-grey color. In thin section the phenocrysts are seen to be olivine, titanaugite, and plagioclase, the latter in places zonal and ranging from $Ab_4An_5$ to $Ab_5An_3$. A little orthoclase occurs. A chemical analysis is given.

Rocks of the third type are alkali dolerites.

ALBERT JOHANNSEN

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WATSON, THOMAS L., and HESS, FRANK L. "Zirconiferous Sandstone near Ashland, Virginia, with a Summary of the Properties, Occurrence, and Uses of Zircon in General," *Univ. Virginia Pub., Bull. Phil. Soc. Charlottesville*, I (1912), 267–92.

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WATSON, THOMAS L. "Kragerite, a Rutile-bearing Rock from Krageroe, Norway," *Amer. Jour. Sci.*, Fourth Series, Vol. XXXIV, 509–14.

Kragerite was briefly described by Brögger in 1904 as a new member of the aplite series and a differentiation product of a gabbro magma. As described by Watson the rock is megascopically medium-grained granitic, and light in color. The prominent constituents are light-grey and pink feldspar, black rutile, and a little quartz. The rutile is in small grains partly disseminated but mostly segregated along roughly parallel lines which give the rock a streaked or banded appearance. The minerals are albite-oligoclase predominant with a little microcline and orthoclase, rutile, and a little quartz and ilmenite. In the rutile-rich portion rutile is predominant accompanied by biotite partly altered to chlorite, apatite, and an altered mineral probably feldspar. The rock occupies a new position in the quantitative system.

E. R. LLOYD

WEINSCHENK-CLARK. *Petrographic Methods.* McGraw-Hill Book Co., New York, 1912. Pp. xx+396, figs. 371.

This work is the authorized English translation of the third edition of Weinschenk's *Anleitung zum Gebrauch des Polarisationsmikroskops*, and the second edition of *Die Gesteinsbildenden Mineralien*. The English title is rather misleading in that it promises less than is given in the book.

The translation follows the German text closely enough to be correct, yet is free enough to be easy reading. Part I begins with a description of lenses and microscopes, and gives instructions for testing and adjusting them. The following one hundred pages are devoted to methods of observation in ordinary, and in parallel and convergent polarized light. Many methods are presented, and the phenomena observed and conclusions to be drawn from them are given, although but little theoretical explanation is attempted. The first part closes with an appendix giving descriptions of rotating, heating, projecting, photographic, and drawing apparatus.

The second part takes up the cutting of thin sections, the separation of mineral constituents by various chemical and physical means, and methods of micro-chemical investigation, staining, determination of specific gravity, etc. The chapter on the development of rock constituents is extremely valuable for beginners, giving excellent figures of various textures (called structures by the translator), and describing intergrowths, inclusions, and so on. The descriptive portion of the book consists of 139 pages with 153 figures, including line drawings of crystal forms and half-tones of thin sections. The descriptions of the various minerals are short but good, and give the principal characteristics. The fact that unusual rock minerals are omitted is to be commended. The methods for the determination of the feldspars are given rather too briefly, however. The volume concludes with 36 pages of tables for the optical determination of minerals.

The book is well printed on good paper and the cuts have come out fairly well, although, in avoiding the annoying glaze of the paper of the German original, much detail has been lost in the half-tones. The loss here seems greater than the gain. Typographical errors, especially under the illustrations, are numerous. On the whole the book is an excellent one and is extremely well adapted to classes beginning the study of microscopical petrography.

ALBERT JOHANNSEN

# *Reviews*

*Underground Water Resources of Iowa.* By W. H. Norton and Others. Iowa Geological Survey. Vol. XXI, Annual Reports for 1910 and 1911. Pp. 28–1186.

This report treats of the sources, conditions of occurrence, chemical ingredients, and amount of the underground waters of Iowa. The waters are considered under three heads: (1) artesian waters, which rise within the tube because of hydrostatic pressure; (2) waters of the country rock; and (3) waters of the drift. Important conclusions regarding these, especially the first, are based upon chemical analyses, deep drillings, and the structure and lithology of the rocks. The state is arbitrarily divided into eight districts, and more or less specific information is set forth for each.

The principal aquifers noted are the Saint Peter and the Prairie du Chien formations of the Ordovician system, and the Jordan, Dresbach, and underlying sandstones (unexposed) of the Cambrian. Superiority is generally ascribed to the Saint Peter, chiefly because it is efficient, accessible, and identifiable over about three-fourths of the state; it, however, is not tapped in the southwestern part, where it lies at great depth and its waters are likely to be mingled in the wells with the highly mineralized waters of the Carboniferous strata. In the western part of the northwest district the Dakota sandstone is a boon to good water conditions. The Paleozoics, especially the lower members which outcrop in Wisconsin, Minnesota, and Northwestern Iowa, dip gently to the southwest in the form of a wide, open trough which leaves the state at the southwest corner. The strata, however, have sufficient variations in structure and lithology to make forecasts somewhat uncertain. The water of artesian wells of the northeast quarter of the state is said to be the purest.

Reasonable consideration is also given to the water conditions of the country rock and drift, and a list of typical well-logs in the townships of each county is published. But the main stress is laid on municipal and industrial supplies, as evidenced by the frequent advices and cautions concerning the procuring of the same. Maps and structure sections clarify the geologic horizon of the important aquifers.

The book is of great value to the state for its clear exposition of the elemental factors entering into the artesian conditions of Iowa, for its appeal to the people to pursue intelligent methods in obtaining their water-supply, and for its emphasis on the increasing necessity of securing drinking-water free from organic matter. This creditable volume was planned during the régime of the late state geologist, Samuel Calvin, and completed under his successor, G. F. Kay. The work was carried on by the State Survey in co-operation with the United States Geological Survey.

M. M. LEIGHTON

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*The Coal Deposits of Missouri.* By HENRY HINDS. Missouri Geological Survey, Vol. XI, 2d Series, pp. 503; pls. 23; figs. 97; maps 7.

The present volume which is the result of co-operation between the Missouri Geological Survey and the U.S. Geological Survey, concerns itself with an economic discussion of the coals of Missouri. Quite properly, a mere outline of the stratigraphy is given and the deeper scientific problems are to be presented in a later report.

The arrangement of the volume is admirable. A short general discussion of the stratigraphy and structure is followed by a chapter on the mode of occurrence of the coals and a description of the different beds and fields. Statistics are presented showing production for various periods. The detailed report by counties arranged alphabetically, is a very desirable feature. Most of the letters of inquiry received by state surveys refer to counties, and it is thought that the grouping of detailed information into county units best meets the needs of the average reader.

Separate chapters are devoted to the quality and efficiency of the coals. In general, the fixed carbon and heat value decrease gradually across the state from south to north and west, the best coals occurring where the Ozark uplift had its greatest devolatilizing effect. Unfortunately, in the chapter on chemical analysis, it is not always clear whether figures given represent values "as received," "air-dried," or "moisture-free." In the tabulated analyses, emphasis is placed on "air-dried" values, whereas most engineers and consumers now compare coals either "as received" or on the "moisture-free" basis. On the latter basis, the coals of the entire state contain an average of 12,363 B.t.u. Tabulated results of tests on steaming, under boiler, for producer gas, on washed coal, and on coking and briquetting are presented in the final chapter.

In districts where quadrangles have been surveyed topographically, full-size lithographed sheets are used to present the geologic features. Many of the figures are graphic sections showing the physical characteristics of the coal beds. A large geologic map of Missouri is included.

It is estimated that the original coal tonnage of the state, not including beds or parts of beds less than 14 inches thick, was 79,362,016,000. One hundred and ten million tons have been mined and perhaps 50,000,000 tons have been left in the ground as pillars. Probably 60 per cent of the remaining coal can be recovered, giving Missouri a future production of 47,702,108,400 tons.

The value of such a report to the commercial interests of Missouri can scarcely be overestimated. The author is to be congratulated on the useful and attractive form in which so much detailed information is made available.

F. H. K.